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Final Report
Development of Technology for Hot Drape Forming and Nozzles for Torus Sections

Contract No. NAS 8-11527

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Huntsville, Alabama 35812

FOREWORD

This final report covers the work performed under Contract NAS 8-11527, Control Number TP3-82405 and TP3-82378(1F) from June 1963 to December 1965. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the National Aeronautics and Space Administration.

This contract with the Republic Aviation Division of the Fairchild Hiller Corporation at Farmingdale, New York, was initiated by the National Aeronautics and Space Administration, Manufacturing Engineering Division, George C. Marshall Space Flight Center, Huntsville, Alabama. The contract was administered by Mr. David Hoppers and technical guidance was furnished by Mr. P. Schuerer and Miss Margaret Brennecke.

Mr. Frank J. Hoppe and W. A. Kloiber were the project engineers on the torus segment forming and Mr. William Matlach was the project engineer on the port forming. Mr. Joseph Mainhardt was responsible for overall supervision of both of these projects. Mr. M. Negrin and Mr. David Waldman performed the metallurgical analyses. This work was supervised by Mr. Walter Trepel.

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INTRODUCTION

The introduction of new materials and the increasing demand for very large sheet metal components has created problems in the forming and heat treatment of compound contoured parts within the framework of currently available forming equipment and methods. A specific problem was the necessity for efficiently forming and heat treating large torus tank bulkhead segments to close contour and thickness tolerances.

The concept of hot drape forming employing a unitized ceramic tooling package with the combined capability of hot forming, solution heat treating, quenching, and artificial aging offers an ideal solution, since it permits maximum flexibility in forming and results in minimum distortion during heat treating operations. This method of forming is an improvement over the current state-of-the-art methods such as stretch press, explosive forming, the use of restraining fixtures, etc. , in which large universal type forming and heat treating equipment is required and where the forming and heat treat operations require distinctly different sets of tools. The hot drape forming concept permits "in process" control of material gauge thinout through use of a flexible method of heat zone control. This allows the operator to control at will the exact temperature requirement in different portions of the part during the forming operation to obtain contour conformance with minimum thinout.

The objective of the program was to design and build a self-contained ceramic tool to completely form and heat treat torus tank gore segments and to develop techniques of operation and control to advance the state-of-the-art to permit utilization of the hot drape forming process in other complex forming problems. A further objective was to develop tooling for the forming of flared port openings in the formed torus segments and in sump sections supplied by NASA.

In addition to a new forming technique, this program involved a new material for the formed parts. 7039 is a recently developed aluminum base alloy which was designed primarily for superior cryogenic behavior and ballistics impact use. When combined with the proper heat treatment, it exhibits excellent mechanical properties coupled with the high resistance to stress corrosion cracking which is necessary for cryogenic tankage. In addition, this alloy is easily welded and may be joined by this technique to produce properties which approach values as high as 85% of the parent metal ultimate strength. This feature is particularly attractive for large size, high joint efficiency welded structures, such as these torus tank segments, where post-welding heat treatment is impractical.

7039, however, was designed for use as a plate alloy, and exhibits the best and most reliable response to thermal processing in that form. Almost all of the data available for this alloy at the start of this program, had been developed for plate material. Due to primary fabrication differences between sheet and plate, this data could not be extrapolated directly for the thickness of material used in this program. For this reason, it was necessary to evaluate the behavior of 0. 125" sheet during heat treatment and to verify the properties expected for the various thermal processing techniques available.

To provide data for the selection of the optimum heat treatment, sub-scale test specimens of 7039 were processed at Republic under conditions simulating those to be encountered by the full-size part on the ceramic tool. Stress corrosion data, where available, was obtained from the manufacturer or was taken from the literature. The results of this evaluation are summarized on the following page.

The use of the T-6 treatment in this program was eliminated on the basis of inadequate resistance to stress corrosion cracking. Since virtually no stress corrosion data was available for T-61 sheet and Alcoa presented data which showed T-63 to possess good stress corrosion characteristics and improved mechanical properties over T-61, NASA directed that the T-63 condition be selected as the treatment for use in the torus tank program.

Process*	Developed by	Typical Properties F_{ty}	F_{tu}	% E	Comments
T-6	Kaiser	52	62		Best room temperature mechanical properties.
T-61	Kaiser	47	58		Improved resistance to stress - corrosion cracking with some sacrifice in room temperature strength as compared to T-6.
T-63	Alcoa	50	60		Best combination of stress corrosion resistance and room temperature mechanical properties. The latter however are inferior to T-6 properties

* The three treatments listed above represent those available during the time this program was in progress. Additional processing techniques for this alloy system have recently been proposed by the producers, however, the merits of these processes for hot drape forming have not been evaluated.

SECTION I

DRAPE FORMING

In this program, the hot drape forming process was used to produce thirty-two torus skin segments according to drawing MRD-SK-398 from 7039 aluminum alloy sheet . 125-inch thick. Of these segments, fourteen were to contain flared ports; six 3-1/4-inch diameter and eight 20-inch diameter as indicated in drawings MRD-SK-396 and 15-A-X-1110 (see Figure 1). In addition, four 3-1/4-inch-diameter flared ports were to be formed in sump sections supplied by the National Aeronautics and Space Administration, per drawing GMT-13804.

The program was divided into five phases as follows:

PHASE I	-	Design of Tooling for Torus Segments
PHASE II	-	Manufacture of Tooling for Torus Segments
PHASE III	-	Qualification of Tooling and the Manufacture of Torus Segments
PHASE IV	-	Development of Preform Geometry for Flared Ports
PHASE V	-	Manufacture of Tooling for Flared Ports and Forming of the Ports

FIGURE 1. Representation of Torus Test Tank MR3562

A. TOOLING AND EQUIPMENT

The concept of hot drape forming entails the marriage of an integrally heated ceramic die with a hydraulically actuated stretch wrap press. This, together with attendant controls, power, hydraulic and water supplies, comprise the entire forming and heat treating packing (see Figure 2 below). Descriptions of the various tool and equipment elements follow.

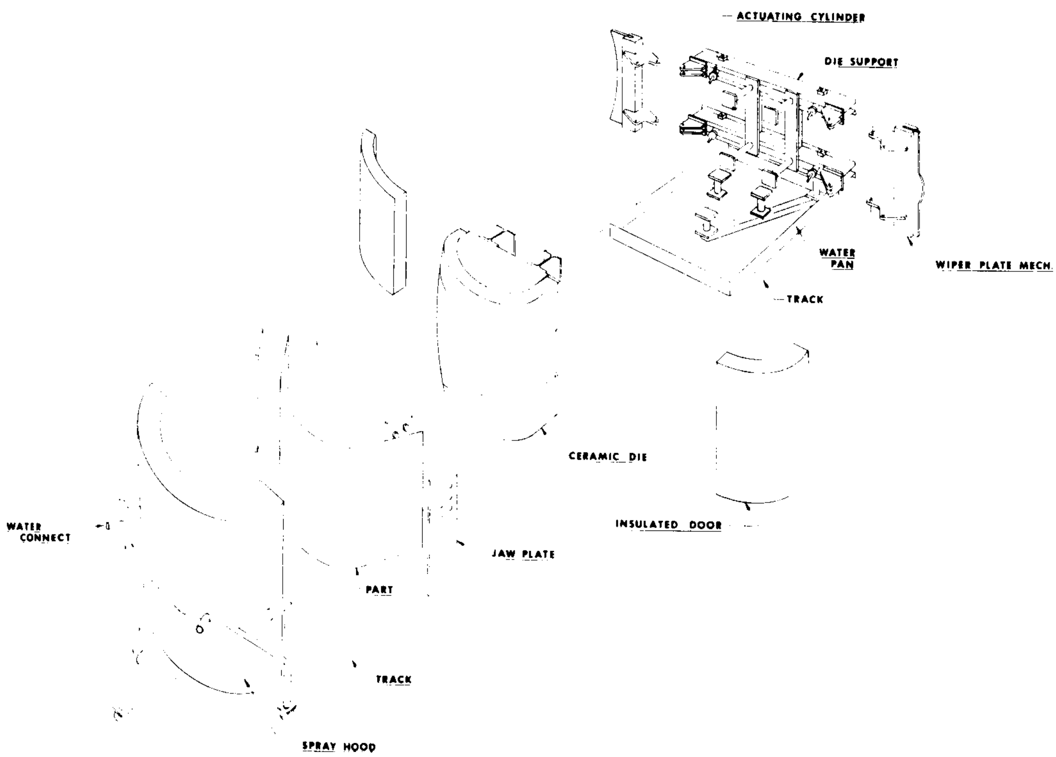


FIGURE 2. Drape Form Tooling

1. CERAMIC DIE

Structurally the die is constructed of a heavy welded steel base which imparts maximum rigidity and contains support legs and attachment provisions. The die surface consists of a fused silica cast glasrock cement which is poured in place and which is backed up by shaped, dense glasrock foam blocks cemented in place. These blocks act both as a compression support for the die face and serve to insulate the welded steel base and prevent heat transfer into the structure. Uniformly spaced clearance holes are cast 3/8-inch below the die surface. Nichrome V heating wires are run through the holes to provide heat for the forming and the heat treating operations. A total of eighteen thermocouples are embedded in the die to sense the temperature in different locations (see Figure 3).

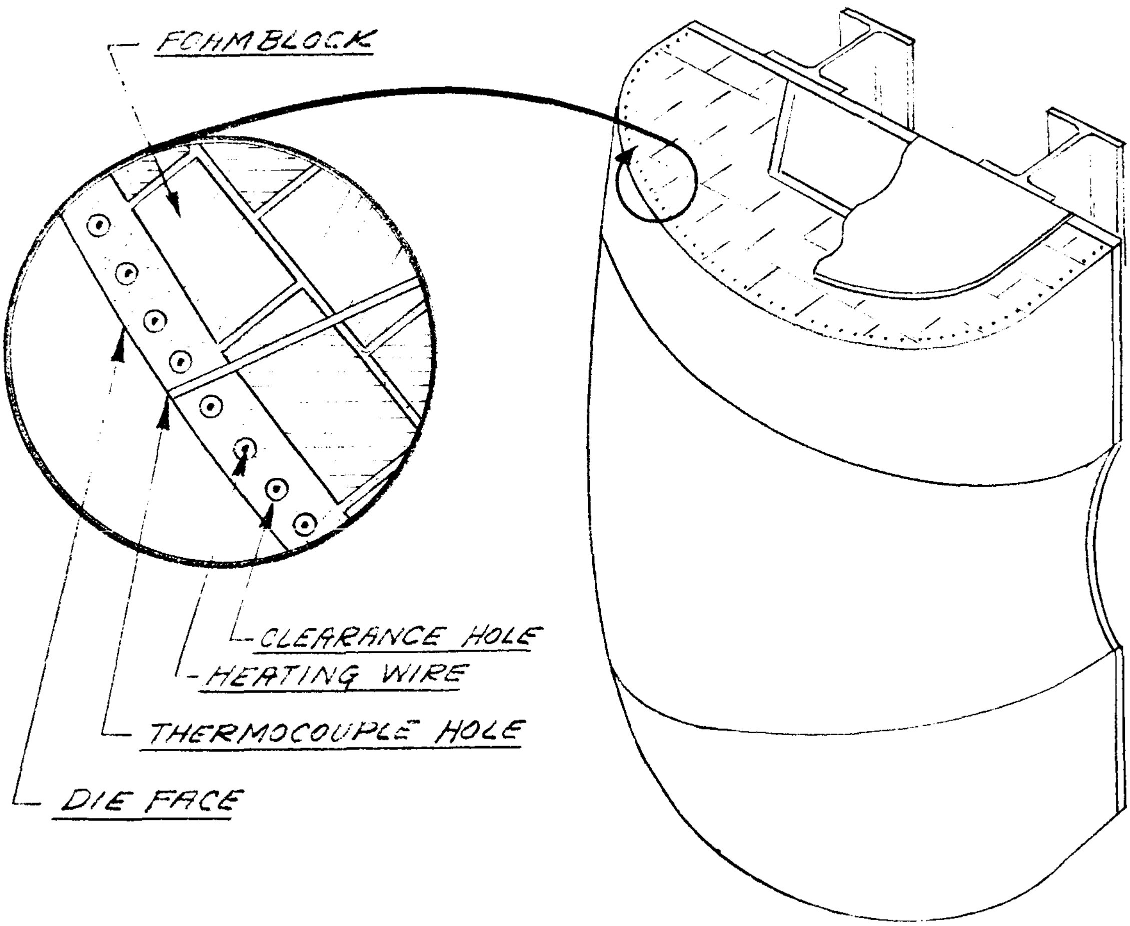


FIGURE 3. Ceramic Die

The ceramic die is divided into the heat zones shown below:

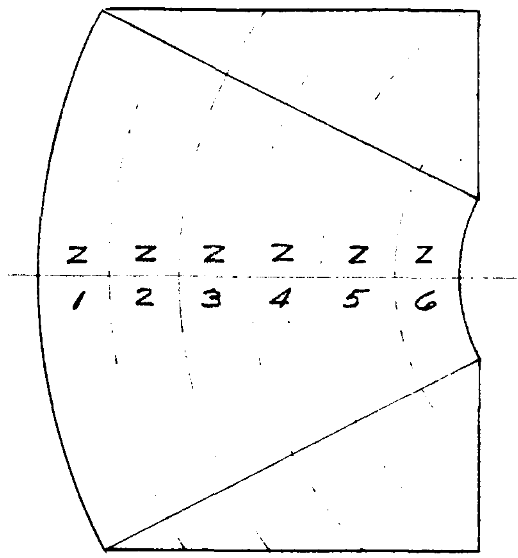


FIGURE 4. Heat Zones

Each of the six zones are wired with forty Nichrome V resistance heating wires, and are connected to provide for separate heat control. The distinct heat zones permit the operator to vary the temperature in different zones during the forming operations. This in turn varies the strength of different areas of the part being formed and controls the amount of stretch in each zone. A part of more uniform thickness is the result. Zone heating control also permits a more uniform part temperature during the solution heat treat and aging operations (see Figure 4 above).

2. DIE SUPPORT AND CYLINDER MOUNT

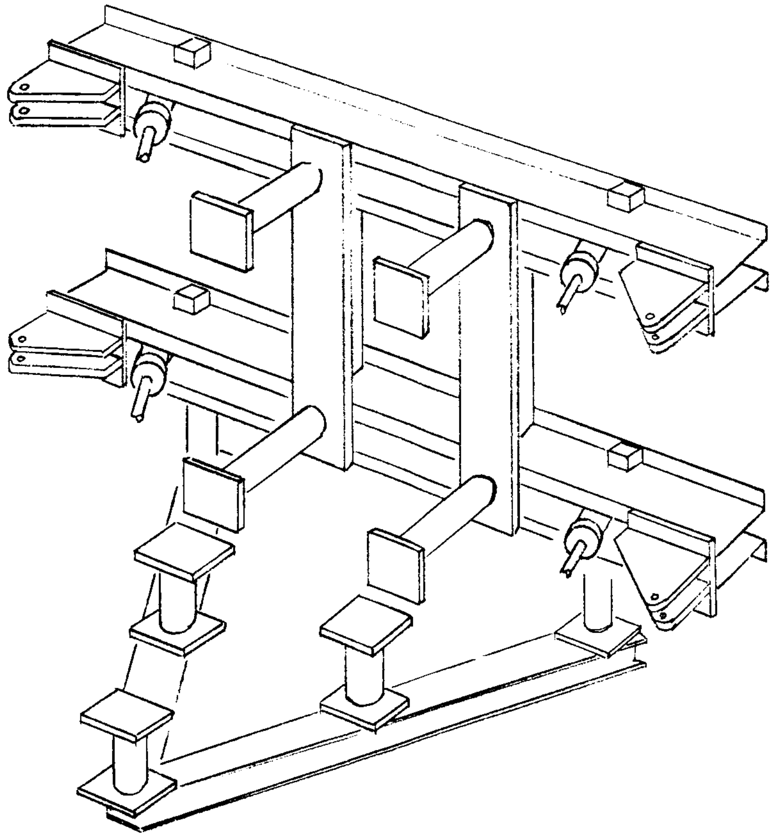


FIGURE 5. Die Support and Cylinder Mount

The die support and cylinder mount is a welded steel structure that serves to hold the die and supports the wiping plate and actuating mechanisms for the forming operation (see Figure 5).

3. WIPER PLATE AND JAW MECHANISM

The steel wiper plate and jaw mechanism serves as gripping jaws to hold the sheet being formed. They are hinged to the die support and cylinder mount and when actuated by the action of the hydraulic cylinders, they stretch wrap or drape the material around the die. Each wiping plate is actuated separately or they may be rotated in unison. The jaw mechanism is designed to facilitate rapid release of the part after solution treatment and quenching to insure that overaging does not occur due to contact with the residual die heat (see Figures 6, 7, and 8).

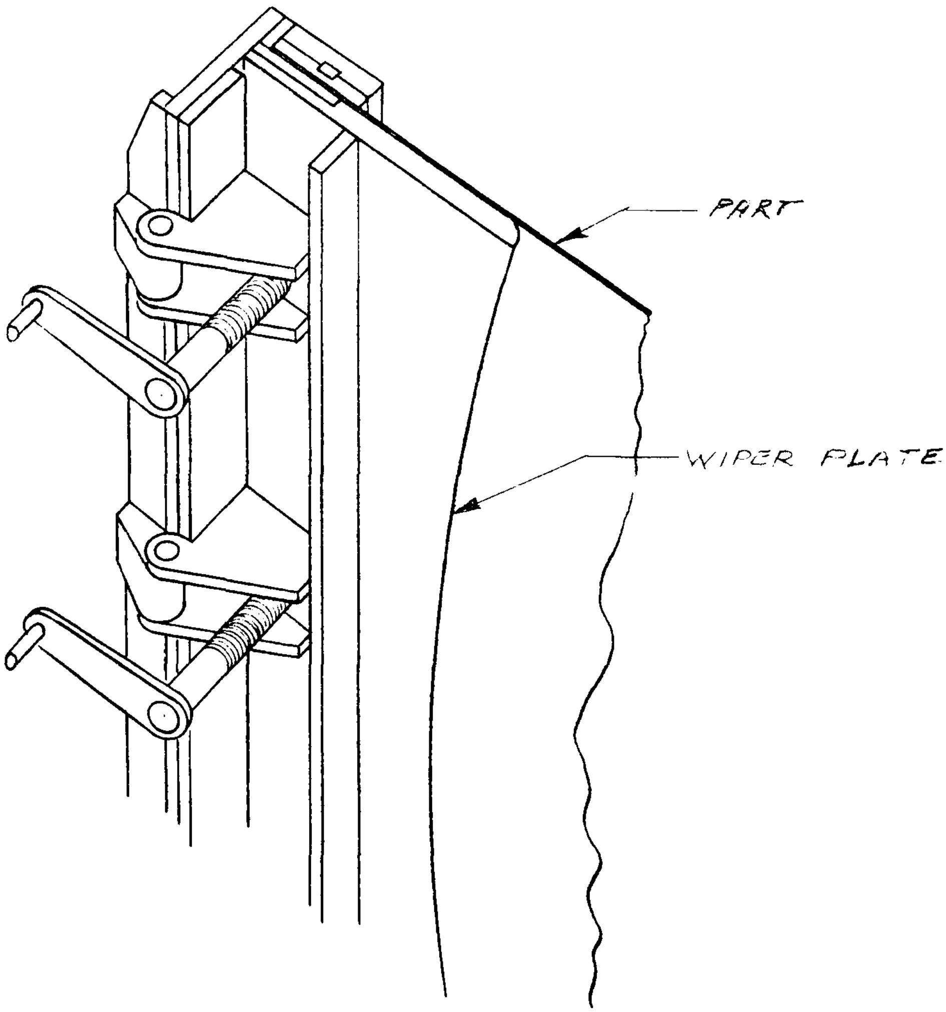


FIGURE 6. Wiper Plate

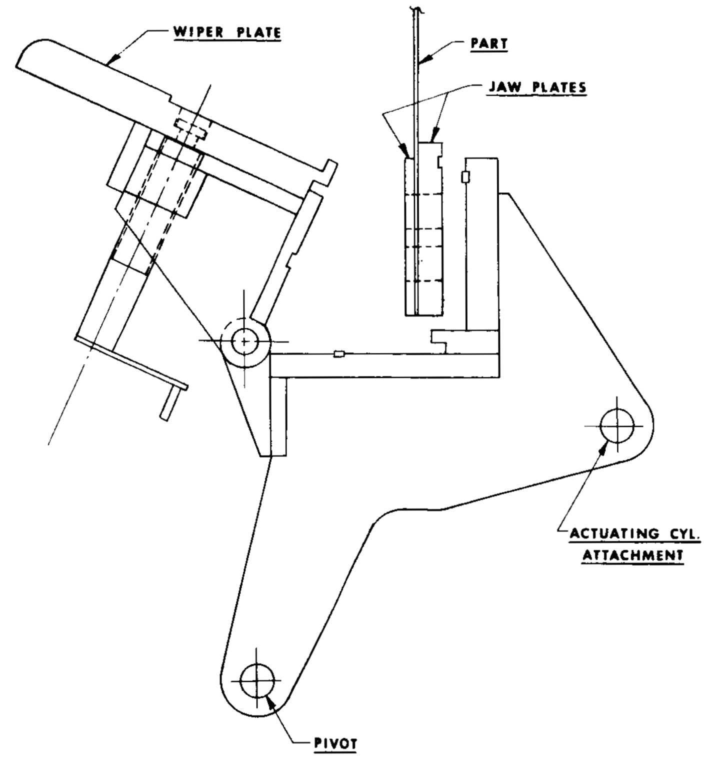


FIGURE 7. Jaw Mechanism

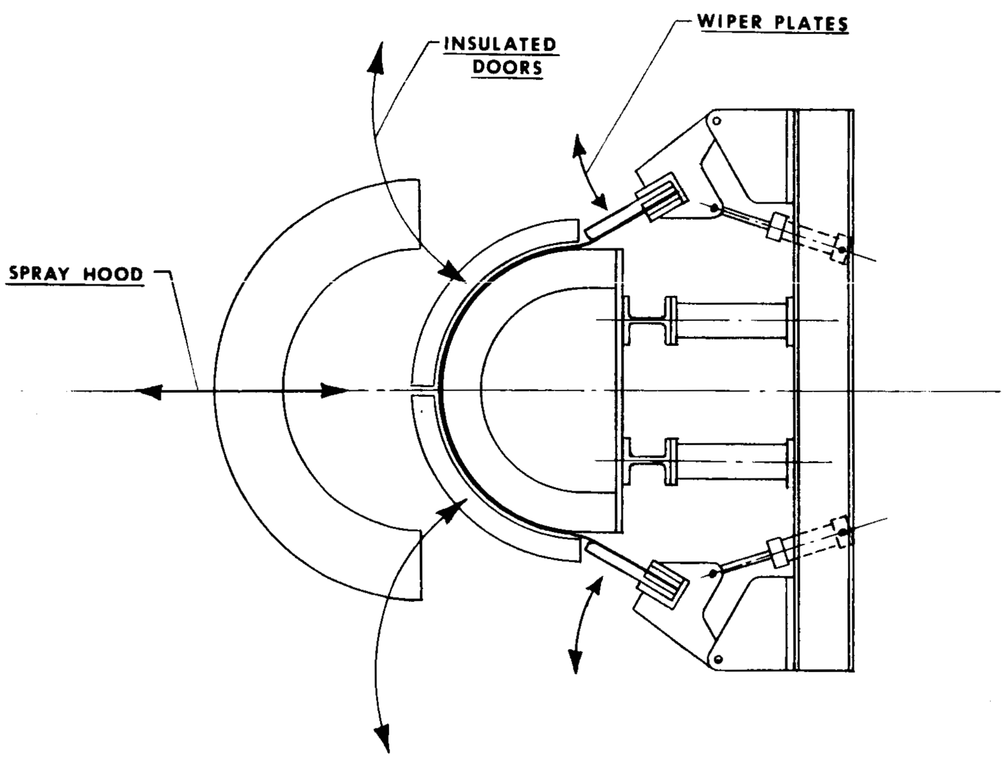


FIGURE 8. Illustration of Drape Form Operation

4. INSULATED DOORS

Insulated doors, Figure 9, are used during the solution heat treat operation to minimize radiation heat loss and to insure a uniform temperature throughout the part. They are of sheet metal construction with a six-inch layer of insulation attached to the concave surface. A simple hinge arrangement allows the doors to be rapidly swung out of the way upon completion of heat treat to permit a rapid water quench.

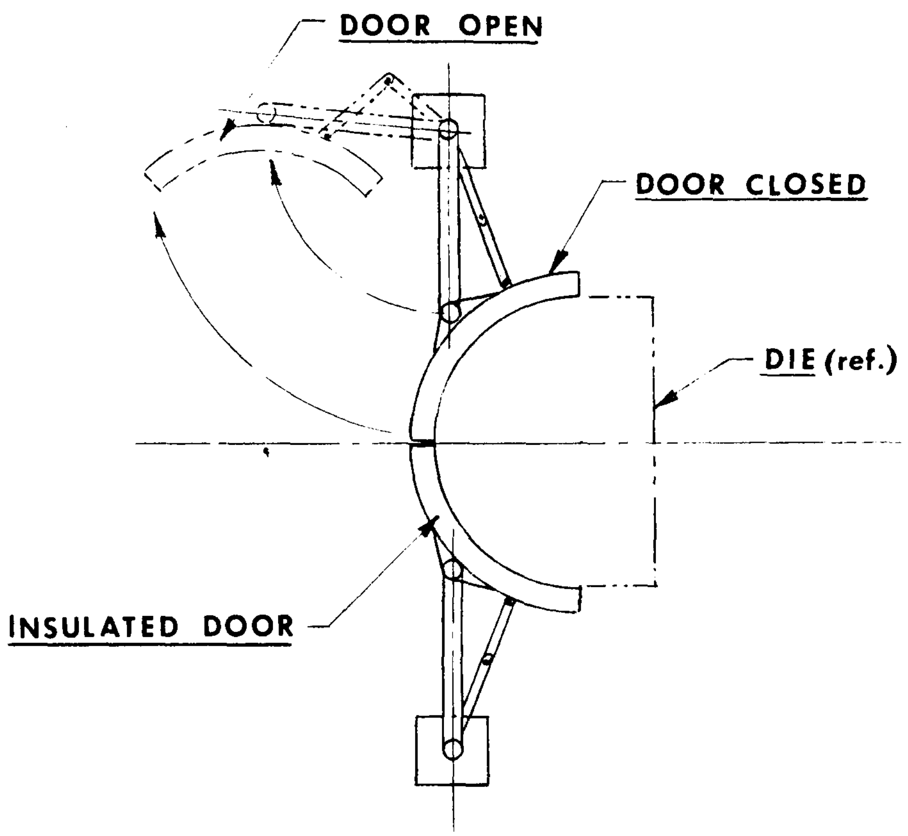


FIGURE 9. Insulated Doors

5. SPRAY QUENCH SHIELD

The spray quench shield, Figure 10, is used to rapidly cool the part upon completion of solution heat treat. A total of thirty-six spray nozzles are mounted on a portable tubular frame to rapidly and uniformly blanket the part with water. A track is provided to guide the hood to its correct position for the quenching operation.

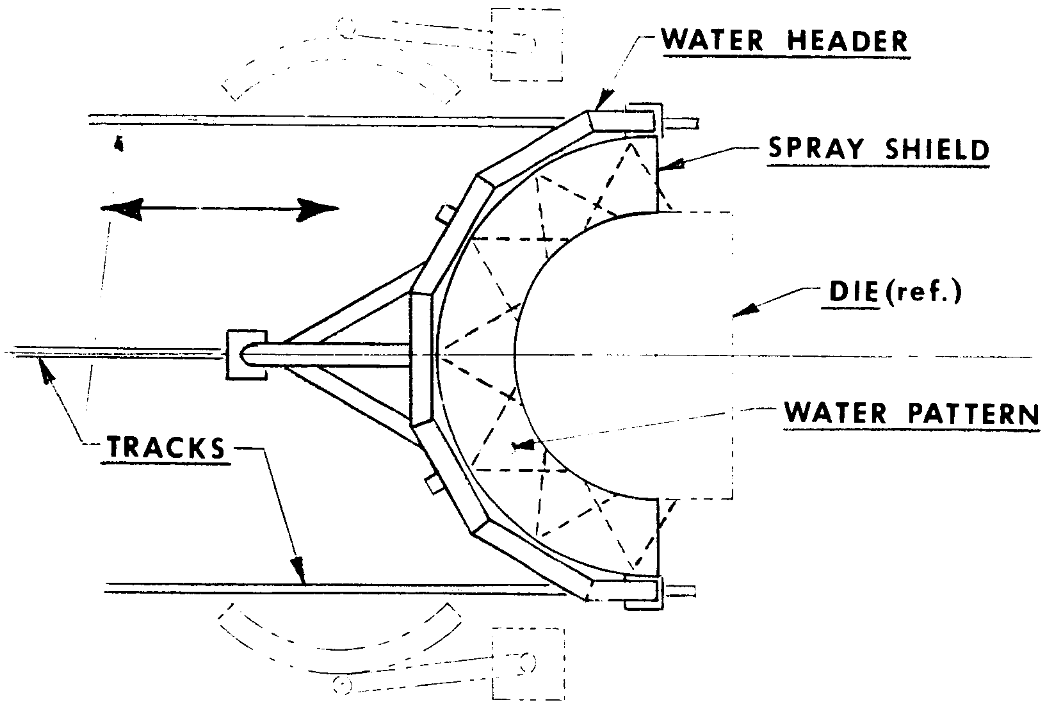


FIGURE 10. Spray Quench Mechanism

6. SPRAY QUENCH TANK

The spray quench tank is used to collect the water used to rapidly quench the part upon completion of solution heat treat. It is of simple sheet metal construction and is located directly under the die.

7. HANDLING SLING

The handling sling, Figure 11, is of tubular welded construction and is used to handle the part during loading and unloading operations.

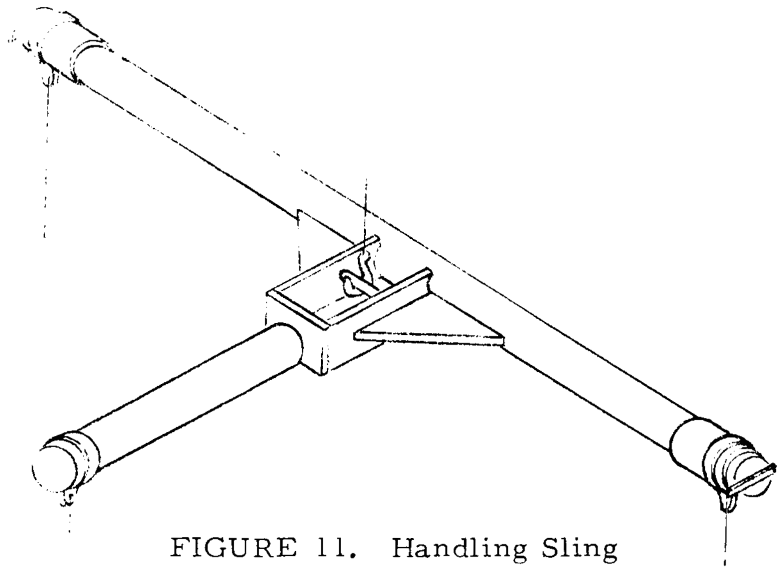


FIGURE 11. Handling Sling

8. CHECKING AND TRIM FIXTURE

The checking and trim fixture consists of a plywood base with a molded glass cloth laminate surface. The formed part is located on the fixture and scribed along the trim line. After trimming and the drilling of tooling holes, the part is checked to the fixture for contour deviations.

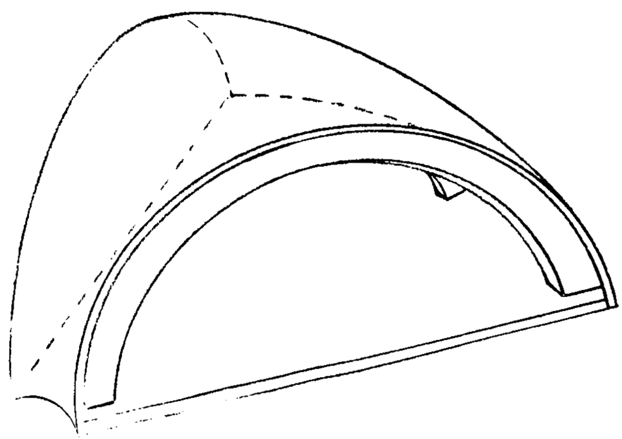


FIGURE 12. Checking and Trim Fixture

9. CONTROLS

a. Hydraulic Power

The wiper plate mechanism is actuated by four Miller hydraulic cylinders with a 6-inch bore and an 11-inch stroke and a rated capacity of 5000 psi. The cylinders are divided into two banks, one bank for each wiper plate. The operating hydraulic pressure of 3500 psi is supplied by a portable 30 hp Sprague hydraulic mule with a capacity of 20 gpm at 2500 psi and 12 gpm at 5000 psi. The system is designed to permit the remote control actuation of each bank of cylinders incrementally, either separately or simultaneously, in either direction. A pair of calibrated scales is affixed to the structural support to indicate the position of the wiper plate mechanism and to insure reproducibility in forming operations.

b. Water System

The water quench system with a capacity of 250 gallons per minute is supplied by four 3-inch lines feeding from the main plant supply line. A solenoid valve in the main line is activated by a switch in the electrical control system. A safety interlock prevents the action of the solenoid valve until the power supply to the heating elements has been shut off. A separate water supply pipe mounted along the top edge of the die is used to flush the surface of the die to insure that the temperature remains below the precipitation hardening range in the interim between quenching and part removal.

c. Electrical System

The power supply and temperature controls are operated through two 45 KVA-440 volt and Weltronic control units. Each unit contains three controllers for a total of six used to control the six separate heating zones in the die. Temperature feedback from the die is accomplished through a total of eighteen thermocouples (three in each zone) embedded in the die. Each controller has its own recorder to keep a record of the thermal history throughout the forming and heat treat cycles.

The Weltronic units control power input to the die by a phase shift system. It eliminates costly maintenance of contactors and operates to prevent over-temperature by modulating the rate of power input.

Control of power input is obtained from the starting characteristics of the thyratron tube. Briefly reviewing the grid characteristics, thyratrons can be negative or positive control tubes. For this discussion, only negative control will be considered (see Figure 13). Static curves as given for D. C. operation must be reshaped for dynamic conditions for A. C. use (see Figure 14).

When the tube grid is allowed to become more positive than the critical voltage, expressed with respect to the cathode and usually a function of the anode voltage, the tube conducts and the anode to cathode voltage drops to approximately 7-10 volts (characteristic tube drop).

Thyratrons in A. C. circuits give continuous load control. When the grid voltage is out of step with the anode voltage (180°), it is always more negative than the critical value so no current flows. When the grid voltage (Figure 15A) arrives 100° out of phase, conduction takes place for a little less than 1/4 cycle, or 1/2 cycle in the case of inverse parallel connection of two tubes. In Figure 15B, with a grid voltage more nearly in phase, the tube is turned on earlier giving a longer current pulse. When the grid voltage is exactly in phase, the tube conducts for the full positive portion of the cycle.

The phase shifting of the grid voltage to intersect the critical voltage curve is accomplished in the circuit of Figure 16. The inductor X and resistor R are connected in series across the supply transformer. The grid voltage developed by the grid transformer connected between the junction and the mid tap point of the supply transformer. In the case where the resistance is equal to the reactance, the voltage applied to the primary of the grid transformer is approximately 90° out of phase with the anode to cathode voltage. This grid voltage can be shifted either way by change in either R or X of the two branches, resulting in voltages $E_R 1$, $E_X 1$.

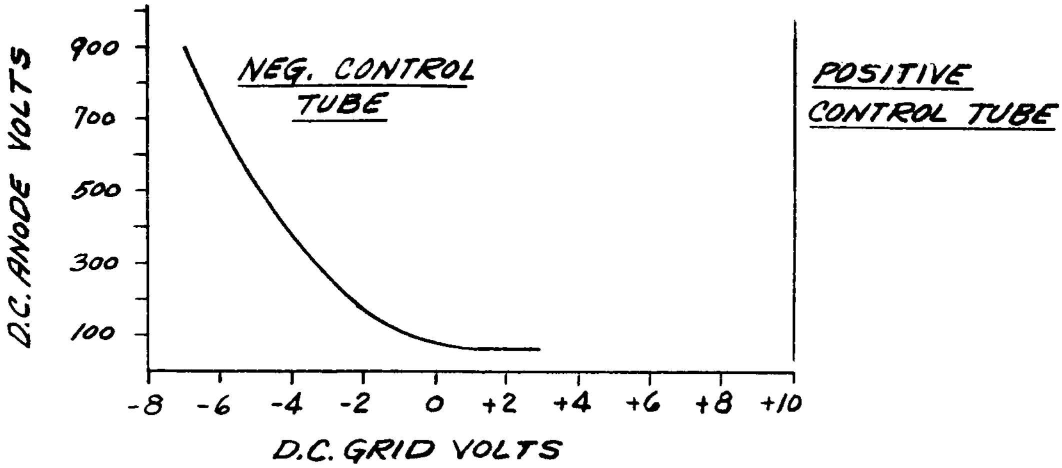


FIGURE 13. Starting Characteristics

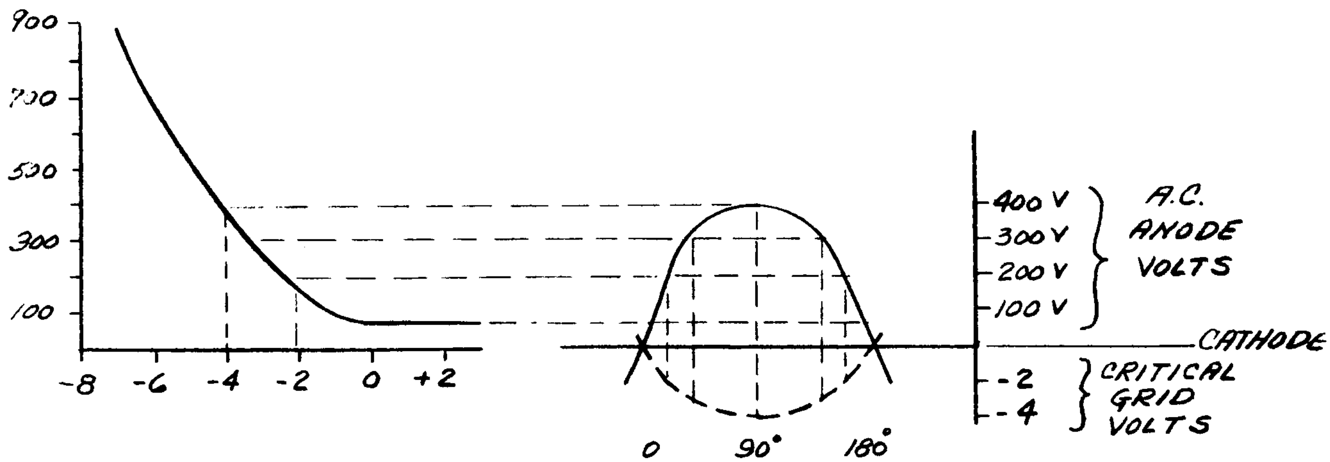


FIGURE 14. Dynamic Change for AC

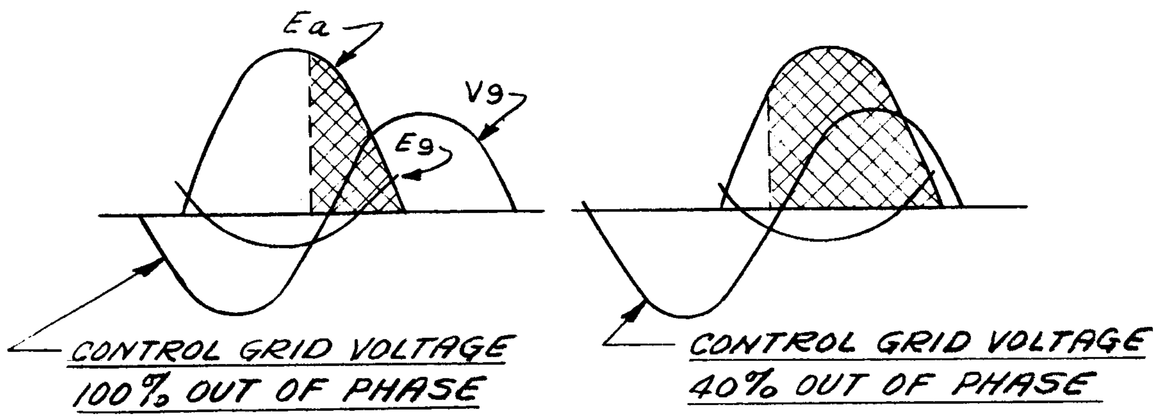


FIGURE 15-A

FIGURE 15-B

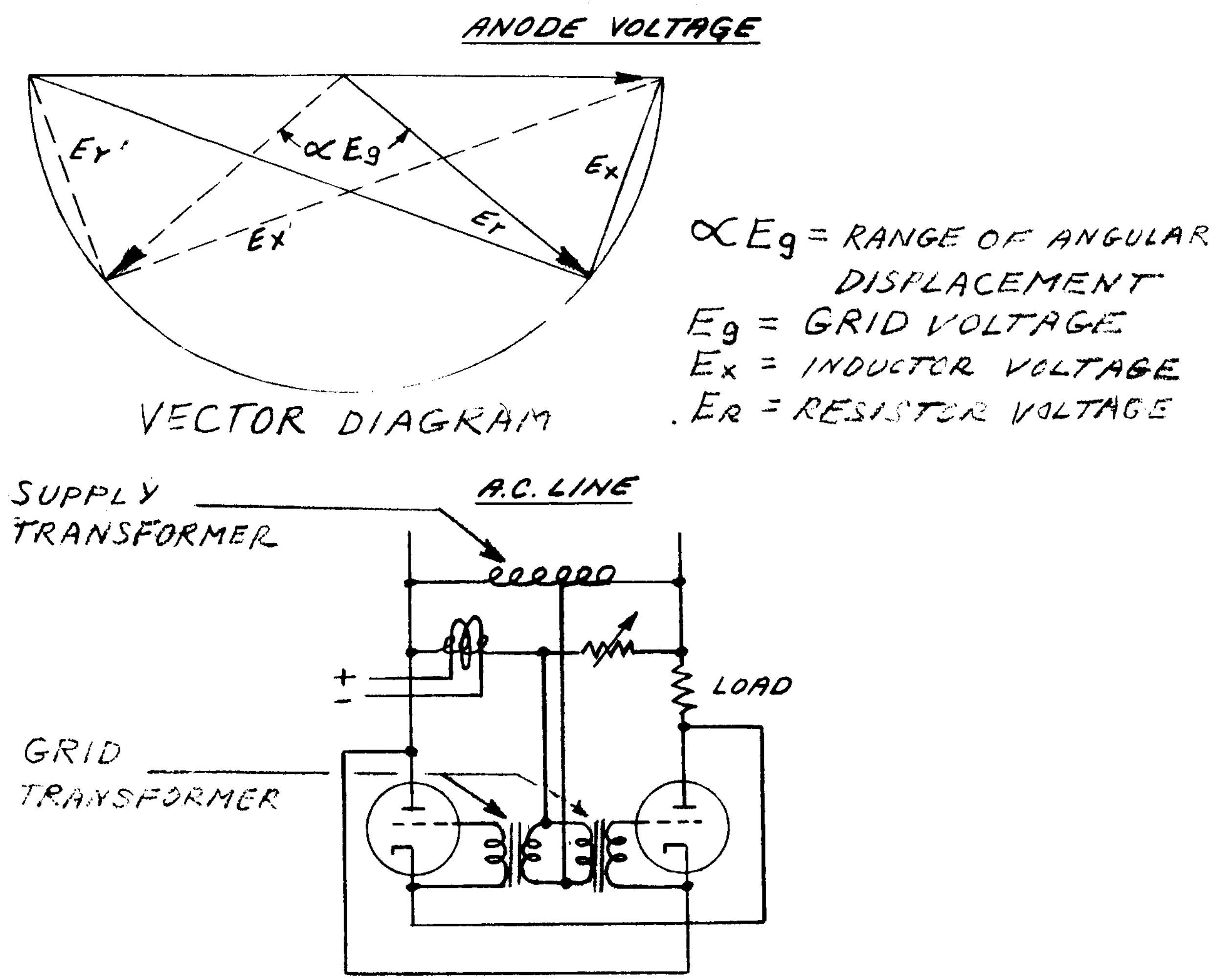


FIGURE 16. Phase Shift Control

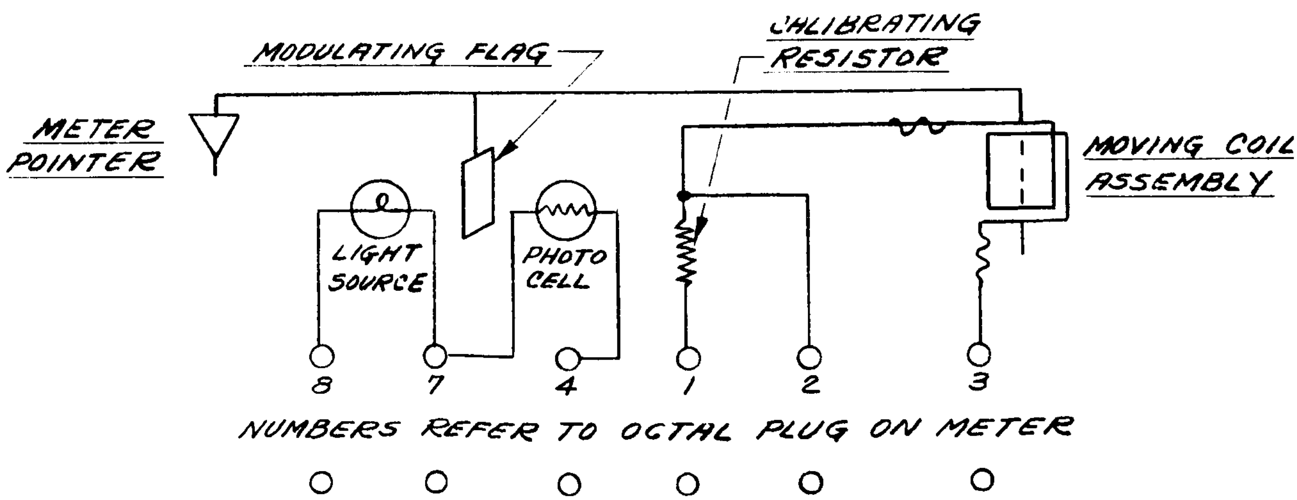


FIGURE 17. Meter and Photo Cell Circuits

The change in X is brought about by the DC signal voltage applied to the DC winding of the inductor (saturable reactor). If the value of current in the DC winding is low, the inductance is high compared to the resistance R. On the other hand, higher values of current in the DC winding reduces the inductance to a value which is low compared to the value of R.

The DC control current for the reactor is supplied by the temperature controller for each heat zone (see Figure 17). The temperature indicator controller consists of three circuit elements. First the millivoltmeter movement and thermocouple source of E. M. F. The voltage generated by the heated thermocouple causes deflection of the meter and movement of the scale pointer. Secondly, the photo cell circuit in which a light source is mechanically interrupted by a flag on the indicating pointer of the millivoltmeter as it moves up to the set point of the instrument. A small light source and photo cell are mounted on the set point arm and as long as light falls on the photo cell (low temperature) the maximum current of the photo cell is fed to a magnetic amplifier. When the light source is interrupted only a minimum (dark current) current is available to feed the magnetic amplifier. There is a zone of control where the light is partially interrupted and a modulating effect will be noted rather than a distinct on-off operation. The third element in the chain is the magnetic amplifier in which the low energy output of the photo cell is boosted to power the phase shift reactor of the thyratron contactor .

B. TOOL MANUFACTURE

To make the die, a full-scale loft layout of the part cross section was produced. From this, a female template of steel was cut to match the loft. The template was then mounted on a pivot or rotating post and was used to sweep out a male mockup of dimensionally stable ultracal (Figure 18). In order to cast and lay up a male die, a female splash (Figure 19) was made from the male mockup and reinforced with a welded pipe structure. Upon drying, the splash was sprayed with clear lacquer (Figure 20) and lined with a thin polyethylene sheet to act as a parting agent. All edges were sealed with vacuum bag compound and the air evacuated to eliminate movement and wrinkling of the polyethylene sheet.

Plywood forms were fitted at the open ends and along the edges of the female splash to retain the glasrock cement and foam block (Figures 21 and 22). The manufacture of the die began by pouring a 3/8-inch thick layer of glasrock cement into the female form (Figure 23). This was accomplished in six stages to prevent the cement from sagging by repositioning the female splash to pour each stage. Then a series of 1/8-inch diameter flexible polyethylene rods were placed on this layer of cement to create the clearance holes for the heating element wires. Spacing and location of the rods was controlled by spacer templates (Figures 24 and 25). The rods were then fixed in position by covering with a layer of glasrock cement. Figure 26 shows the ends of the polyethylene rods extending through the plywood board at the end of the form.

Upon completing layup of the cement and positioning of the polyethylene rods, a series of eighteen 1/2-inch diameter rods were installed to act as spacers for the thermocouple clearance holes. Glasrock foam block was then cut and fitted to the inside surface of the form and cemented in place. Figure 27 shows the blocks being fitted and Figure 28 shows the completed layup of the blocks.

Concurrent with the manufacture of the ceramic portion of the die, the steel base was being prepared. Figure 29 shows the base being welded together. Studs welded to the trapezoidal section serve to key the ceramic

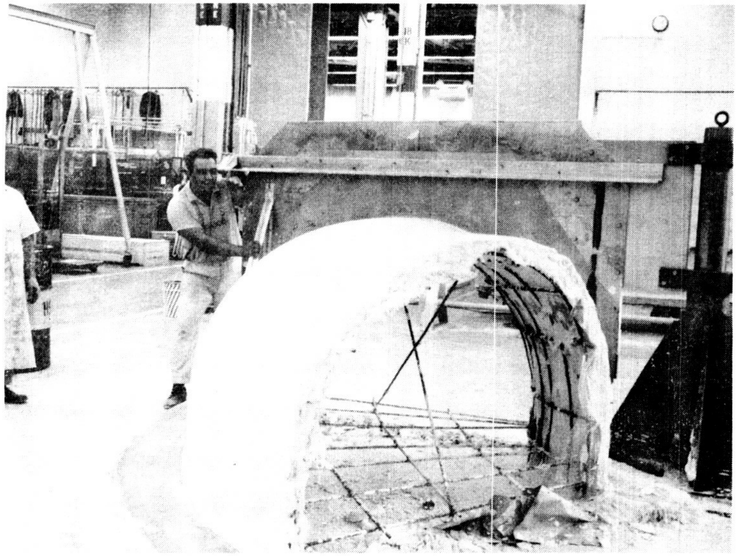


FIG. 18 Male Mockup

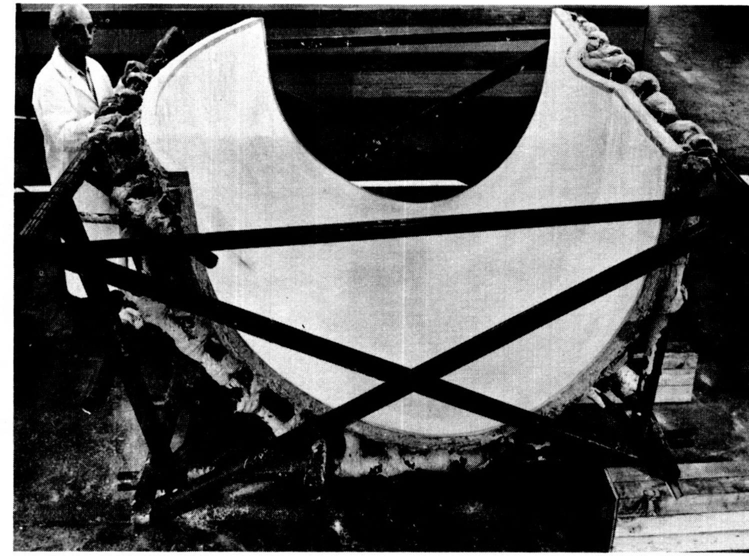


FIG. 19. Female Splash MR3625

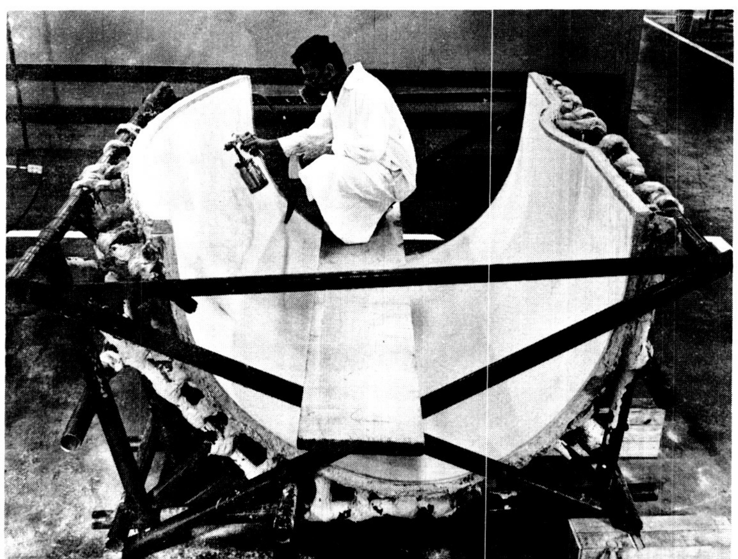


FIG. 20. Applying Lacquer MR3623

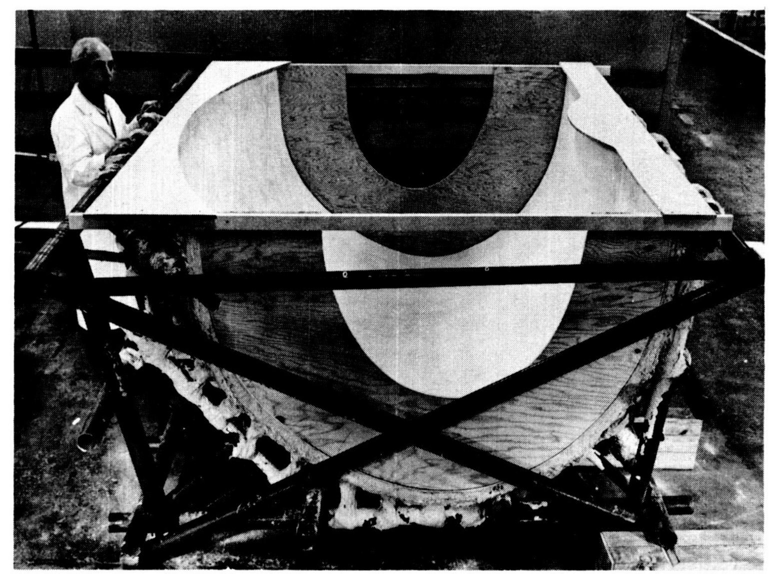


FIG. 21. Plywood Form MR3624

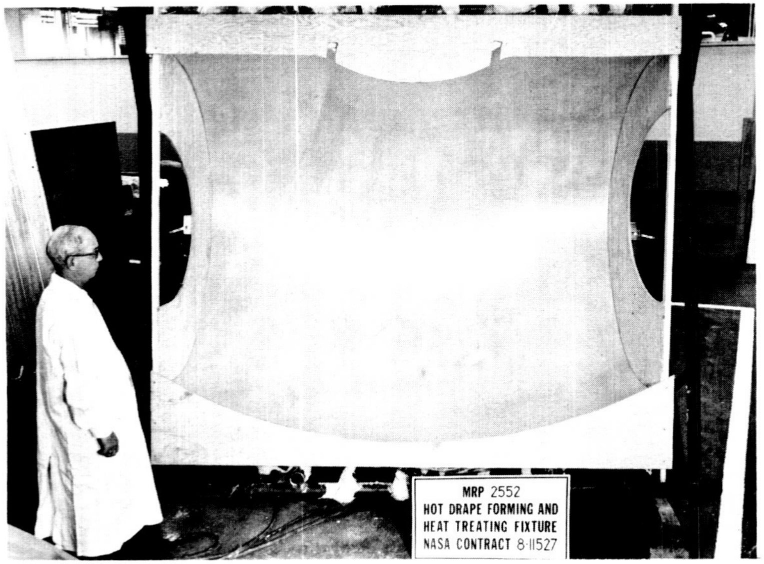


FIG. 22. Plywood Form MR3620

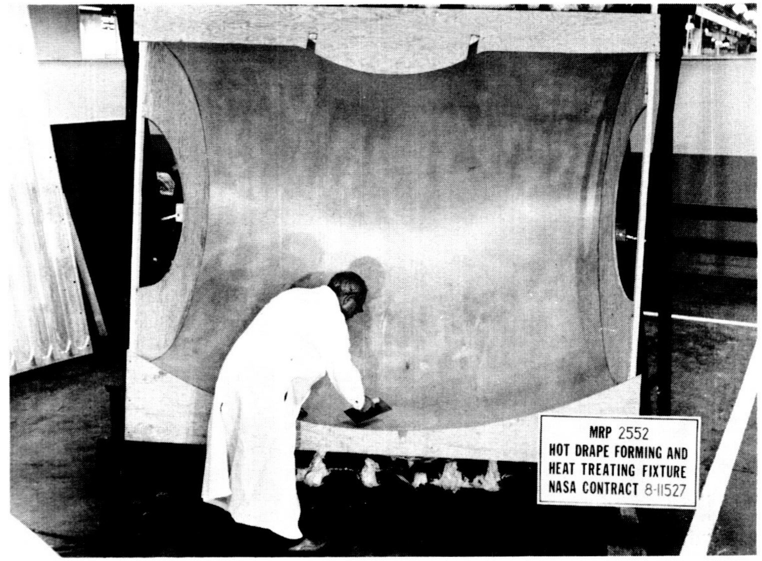


FIG. 23. Pouring Cement MR3619

FIG. 24. Pouring Cement MR3621

FIG. 25. Pouring Cement MR3622

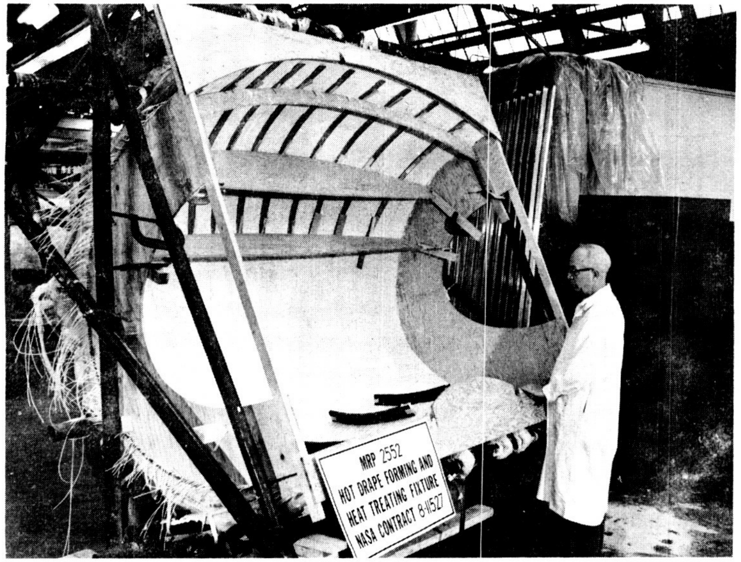


FIG. 26. Pouring Cement MR3649

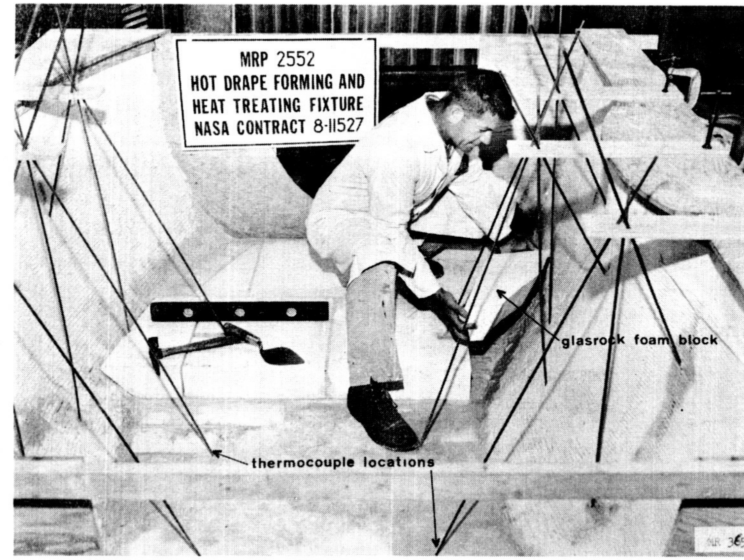


FIG. 27. Locating Foam Block MR3658

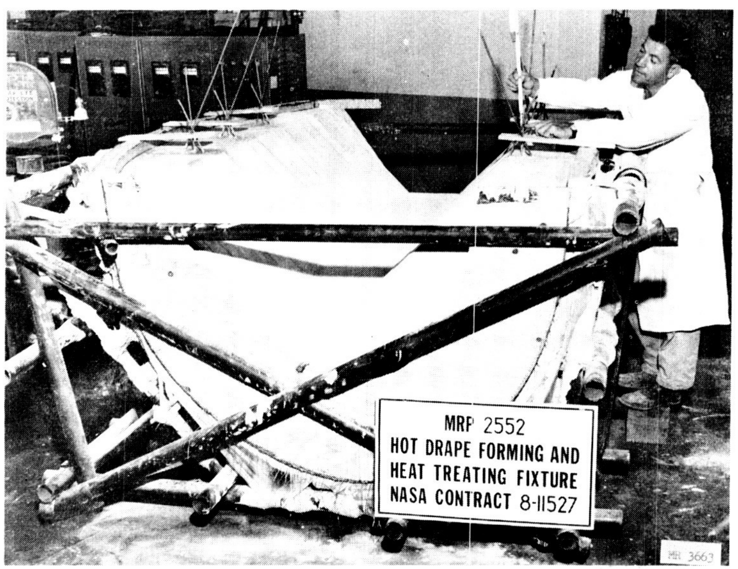


FIG. 28. Foam Block in Place MR3663

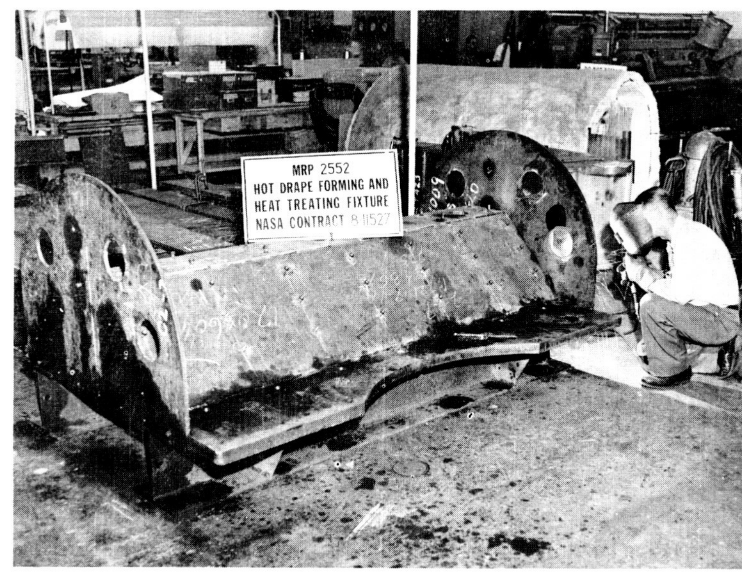


FIG. 29. Steel Die Base MR3662

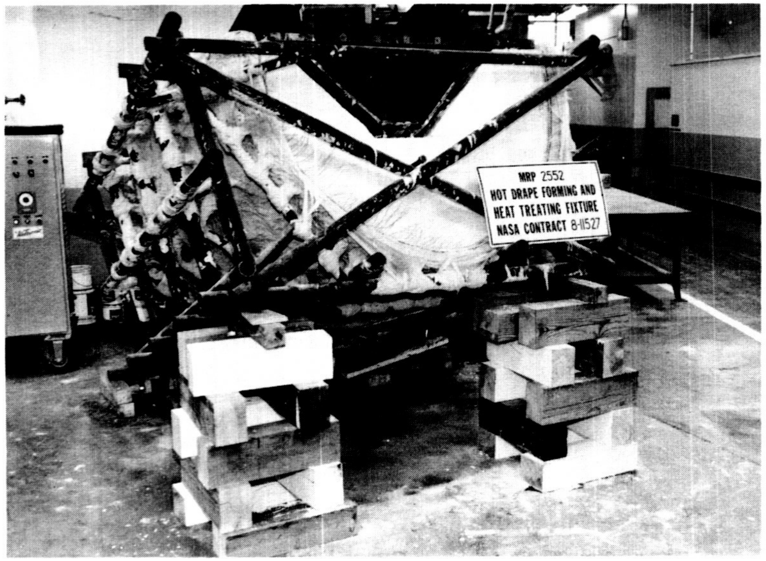


FIG. 30. Positioning Die Base MR3693

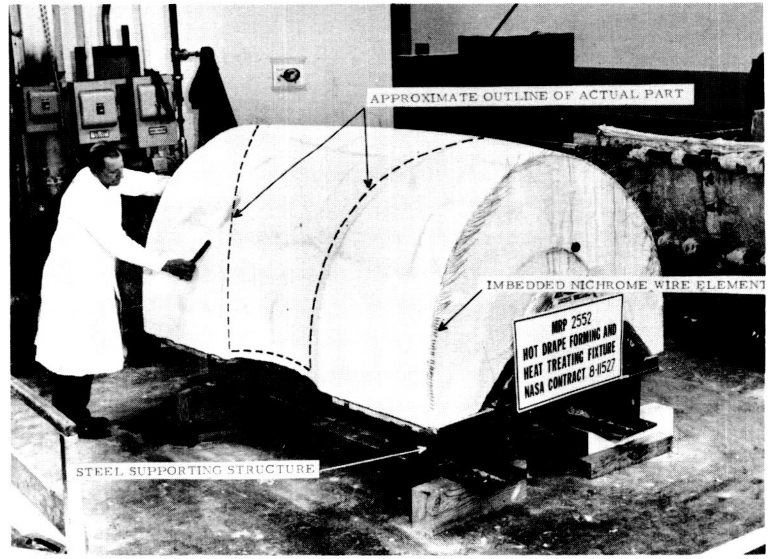


FIG. 31. Patching Minor Imperfections MR3701

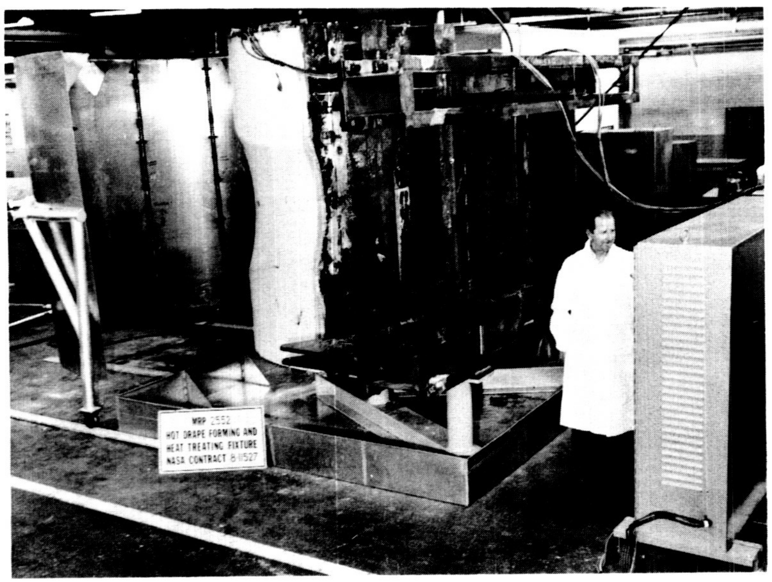


FIG. 32. Back View MR3708

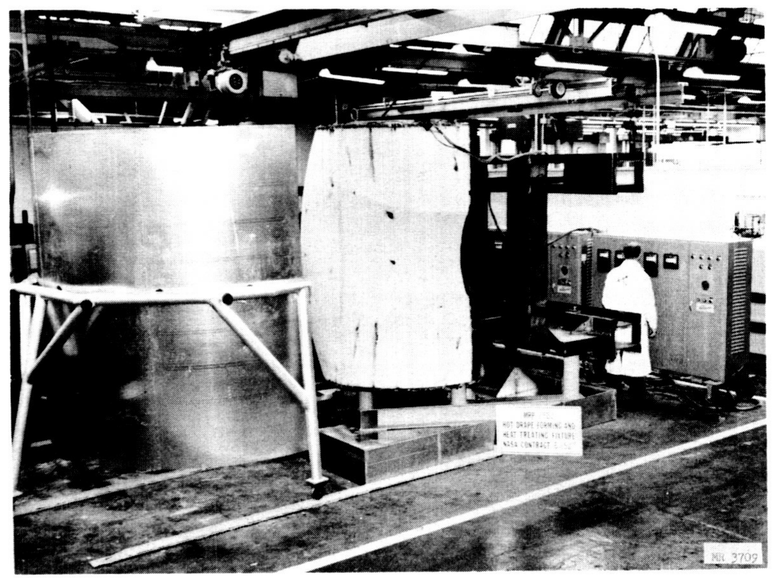


FIG. 33. Front View MR 3709

portion of the die to the steel base. The end plates are made removable to facilitate further assembly procedures.

The steel base structure was mounted above and relative to the ceramic portion of the die. They were then tilted at an angle to permit the pouring of glasrock cement between the two to bond them together. Figure 30 shows them in this position.

After pouring of the cement and the proper curing time has elapsed, the die was removed from the plaster form. Minor imperfections in the die surface were repaired with glasrock cement and the polyethylene rods withdrawn from the die. Nichrome V heating element wires were then inserted in the clearance holes. Figure 31 shows the wires located in place.

Upon completion of the wiring, the die was mounted in a vertical position on three pedestals and securely fastened to the die support and cylinder mount which had been fabricated concurrently with the die (see Figures 32 and 33).

Hanging the hinged wiper plates and gripper mechanism, addition of hydraulic and water lines and the electrical wiring for heating and control completed the assembly.

C. PART FORMING

1. QUALIFICATION TESTS

Preliminary tests of the entire mechanical, hydraulic, electrical and control systems indicated that the die and attendant systems functioned well. Temperatures ranging from 200°F to 400°F were set on the controllers and thermocouple readings indicated a good degree of uniformity of exposed die surface temperature in this range.

Concurrent with the forming tests in which actual parts were formed on the die, a series of correlated tests and investigations were carried out. These included:

a. Metallurgical tests to examine the characteristics of the material and to verify heat treat parameters

b. Lubrication tests to find a suitable die lubricant

c. Insulation tests to arrive at a solution to radiation and heat loss problems

a. Metallurgical

The T-63 Heat Treatment*

The 7039 aluminum alloy is heat treatable to the T-63 condition by precipitation hardening techniques. In this condition, it combines high strength, ductility, and toughness with good weldability and stress corrosion behavior. The chief constituents of this alloy include zinc and magnesium, which are the major contributors to the hardening mechanism. Other elements such as chromium and manganese are present in small amounts for improved corrosion resistance and for added strength.

In order to successfully produce the T-63 treatment in the torus tank segments utilizing the ceramic tool, a five step thermal processing technique was adopted as follows:

- -solution heat treatment
- -quenching to ambient temperature
- -natural aging
- -artificial aging Stage 1
- -artificial aging Stage 2

The reasons for the choice of the particular processing conditions utilized for each of these steps is discussed below. Proof of these practices is presented as a part of the evaluation conducted during the qualification testing which was performed on Segment Number 6.

Solution Heat Treatment

Solution heat treatment was performed in accordance with the manufacturer's recommendations. A metal temperature of 840°F $\pm$ 40°F was used for a sufficient period to accomplish solutioning of the alloying constituents. The minimum amount of time to perform this operation was set at not less than forty minutes, in agreement with the requirements of MIL-H-6084C.

*The T-63 heat treatment was developed by the Aluminum Company of America for alloys of the 7039, X7139, X7106 type. In order to perform this process, it was necessary to arrange a licensing agreement between Republic Aviation Division and Alcoa which prohibits disclosure of the exact details of the process. Alcoa, however, has granted permission (letter dated 4/26/65) for description of the process to the extent it was practiced by Republic.

TABLE 1. THE EFFECT OF SOLUTION TREATMENT TEMPERATURE ON THE RESULTANT PROPERTIES ACHIEVED

Spec. No.	Solution Treatment Temp.	Properties As Quenched *				Spec. No.	Properties As Aged (T-61)			
		F_{ty}	F_{tu}	%e	R_F		F_{ty}	F_{tu}	%e	R_F
271-4	750°F	16.7	42.4	21.0	68	271-500	47.2	58.6	13.5	99
271-5	750°F	18.3	42.2	20.5**	68	271-501	47.7	58.8	13.5	99
Av.	750°F	17.5	42.3	20.8	68	Av.	47.5	58.7	13.5	99
850-3	850°F	17.5	40.9	21.5	66	850-1	47.1	59.0	11.5	99
850-4	850°F	17.5	41.1	21.0	67	850-2	47.6	59.0	13.5	99
Av.	850°F	17.5	41.0	20.3	66.5	Av.	47.3	59.0	12.5	99

* Quenching was performed by immersion in cold water and with agitation.

** Failed outside middle third of reduced section.

Laboratory test specimens (see Table 1) indicated that these conditions were adequate to achieve proper solutioning and that temperatures as low as 750° F and as high as 880° F could also be employed without harmful effects or detraction from the subsequent mechanical properties obtained after aging.

To ensure that the proper conditions of temperature were being used and to determine the thermal uniformity of the part, a network of twenty-two calibrated thermocouples were installed on the qualification part. These were connected to continuously recording multipoint instruments and remained with the qualification part throughout its entire thermal treatment.

Quenching

Alloys of the aluminum-magnesium-zinc system are less sensitive to quenching rate than any other high strength aluminum alloy system. The T-63 treatment takes advantage of this factor, by requiring a controlled rate of quenching to maintain full mechanical property values without sacrificing resistance to stress corrosion cracking. Therefore, as slow a quench as is possible without the loss of mechanical properties is the most desirable condition and a limit of 200° F per second was set as the ceiling for preserving maximum stress corrosion resistance. This rate is in agreement with Alcoa's recommendations for thermal processing of this alloy.

The control of final properties therefore begins with solution treatment and slow quenching to obtain a favorable distribution of precipitate particles, and to establish the proper chemical potential between the grain boundaries and the grain bodies for optimum corrosion and stress corrosion behavior. A rapid quench would yield heavy grain boundary precipitation - which would be unsatisfactory for the corrosion resistance desired. This philosophy of control of precipitate size and adjustment of potential between the grain bodies and grain boundaries is carried further during the subsequent aging steps.

In order to guarantee that a satisfactory quenching rate would be obtained, it was necessary to accurately measure the rate actually achieved during quenching. A high speed strip recorder capable of measuring temperature changes of 1000°F in very short times was necessary.

To meet these requirements, a multichannel recording oscillograph was employed. This instrument uses reflected light beams (from individual, rapid responding moving coil galvonometers) projected on photosensitive paper to record temperature changes as a function of time. At chart paper speeds in the range of 0.25 inches to 64 inches per minute, this was well within the range of quenching rates necessary for the program.

Initial temperature measurements were made with thermocouples attached to the part by a washer and screw arrangement and by spring loaded mechanical means. The results obtained with these methods showed a large degree of scatter, attributable to contact of the thermocouple itself, with the quenching medium.

Thermocouples peened beneath the surface of the metal showed similar results and it was concluded that this method showed little advantage over the screw and washer technique in shielding the thermocouple from the water and steam generated. It was finally decided to shield the thermocouple completely in a metal sheath. The following procedure was used:

1) Thermocouples with fusion welded bead junctions were inserted in the center of an aluminum tube which had a wall thickness equal to half that of the part.

2) This protection tube was then flattened, so that the thickness of the entire assembly equalled that of the part. This ensured that intimate contact between the thermocouple and the tube was achieved (one end of this tube was sealed by welding and the other was sealed with a castable epoxy resin to prevent water from contacting the thermocouple).

3) The tube was spot and seam welded along the full length of the thermocouple to prevent expansion during heating and to prevent the thermocouple from being dislodged from its position.

4) After calibration (by immersion in a molten salt bath at 860°F and in ice water at 32°F) the flattened thermocouple assembly was TIG welded to the part (being careful to maintain intimate contact between the assembly and the contour of the part).

The quenching rates obtained with this thermocouple arrangement for various quenching conditions for 0.125-inch thick aluminum are shown in Tables 2 and 3.

The following procedure was employed to obtain thermal and quenching rate data from the qualification part:

- Shielded thermocouples were prepared as described above and were welded to a previously formed full-size part. Additional thermocouples were installed in twenty-two areas on this part to accurately survey each heating zone (see Figure 54).
- Mounting on the ceramic fixture followed, and the temperature was raised to that required for solution heat treatment.
- The part was held at a metal temperature of 840°F $\pm$ 40°F for forty minutes as temperature readings were taken continuously from the various areas of each zone.
- After solution treatment was completed, the spray quench assembly was moved into position, the power to the elements was disconnected and the part immediately quenched by water spraying.

The thermal data obtained from these operations indicated that all areas within final trim of the part were at temperatures proper for solution heat treatment and that quenching had been satisfactorily performed at a rate of 125°F/second.

Natural Aging

A period of natural aging prior to artificial aging is mandatory for this alloy. This practice increases both the yield and ultimate tensile

TABLE 2. QUENCHING RATES[(1)] OF 0.125-INCH THICK ALUMINUM ALLOY AS A FUNCTION OF QUENCHANT TEMPERATURE

Quenchant	Temperature of Quenchant (° F)	Quenching Rate (° F/Second)
Water	66	680
Water	100	340
Water	140	247
Water	150	224
Water	162	204
Water	176	190
Forced Air 90 psi (78° F)	-	56
Still Air (78° F)	-	3

(1) This data was obtained by immersion in a quenching bath at the indicated temperature. Data obtained on subsize ceramic die is presented in Table III

TABLE 3. QUENCHING RATES OF 0.125-INCH THICK ALUMINUM ALLOY AS A FUNCTION OF QUENCHING TECHNIQUE

Quenching Media	Maximum Quenching Rate (° F/second)
Cold water (60° F) - (immersion with agitation)	1690
Hot water (140° F) - (immersion with agitation)	271
Cold water (60° F) - spray on subsize ceramic die	188
Hot water (140° F) - spray on subsize ceramic die	55
Atomized cold water mist on subsize ceramic die	46
Forced air - free	56
Atomized cold water mist (low rate) on subsize ceramic die	18
Forced air - on die	1.7
Still air	3.0

strengths of the final product and further aids in establishing the proper chemical balance for stress corrosion resistance. The rise in properties begins shortly (within one hour) after natural aging has begun and continues to increase in a logarithmic manner.

The attainment of satisfactory properties requires at least two days of natural aging - preferably longer, since still greater improvement in mechanical property values result with increased natural aging time. Reduction of the natural aging time below two days, however, results in a loss of room temperature tensile properties with a concomitant decrease in cryogenic behavior. A delay of five days is optimum for this process although longer times may also be employed. Natural aging, beyond five days, however, produces only slightly beneficial effects.

For these reasons, all of the 7039 parts processed during the program were subjected to natural aging treatment at ambient temperature for at least five days.

Artificial Aging

-Stage 1

-Stage 2

Artificial aging for the T-63 treatment is performed in two steps over a range of temperatures and times; however, careful control of both these variables is required to yield satisfactory, reliable reproducible results. The process incorporates a low temperature aging cycle (Stage 1) followed by subsequent exposure at a somewhat higher temperature (Stage 2). This treatment differs from another manufacturer's technique (T-61) which requires a controlled rate of heating to achieve property values and stress corrosion resistance.

The purpose of the lower temperature aging in the T-63 treatment is to establish proper precipitation zones for the first or transition precipitation. The higher temperature exposure completes the aging process and causes additional precipitation in the grain boundaries which results in a well-balanced chemical potential throughout the material. This is necessary to further enhance the properties set up previously during the quenching operation, natural aging and low temperature artificial aging.

The conditions employed for artificial aging during this contract were as follows:

Stage 1 225°F ±10°F for 8 hours

Stage 2 300°F ± 10°F for 16 hours

Although a tolerance of ± 10°F was set for this operation, thermocouples fastened to the qualification part indicated that temperature variations were considerably less than this value - the average deviation recorded was less than 5°F.

b. Lubrication Tests

In order to eliminate galling of the aluminum alloy workpiece during forming caused by the abrasive action of the granular surface of the ceramic die, a series of tests were conducted to find a lubricant that would be suitable for this type of service and could be used in lieu of a scuff sheet. The lubricant must be able to withstand temperatures up to 1000°F, possess high film strength and be readily removable from the workpiece.

Test conditions were regulated to simulate production as closely as practicable. A series of 6 x 6 inch typical fused silica ceramic blocks were fabricated to simulate the die. A compressive load of 100 psi was imposed on a 1-inch wide aluminum specimen bearing on the lubricated silica block between heated platens set at 600°F in a hydraulic press. Tension, to cause sliding of the specimen over the die surface, was exerted on the test specimen by a tensile machine (Figure 34). Several different lubricants were applied to the blocks, and test results (Table 4) indicated boron nitride was most suitable.

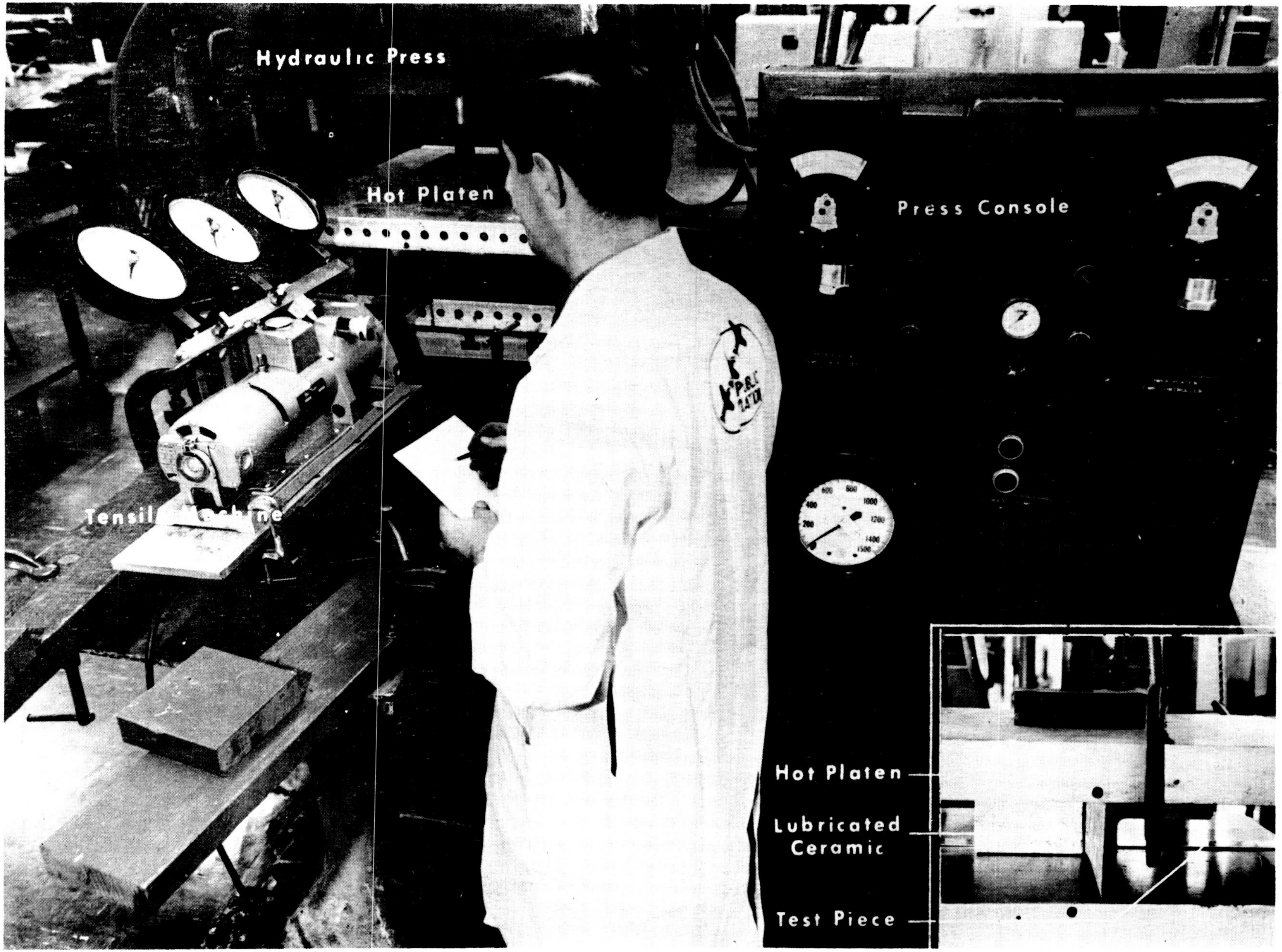


FIGURE 34. Test Apparatus - Elevated Temperature Lubricants MR3893-1

TABLE 4. TEST CONDITIONS - 100 PSI COMPRESSIVE LOAD 550°F TO 600°F SPECIMEN TEMPERATURE

Lubricant	Tension (pounds)	Comments
Dry (unlubricated)	1200	Surface galled. Movement stopped after 1/2 inch
Lubricold (Mica)	400	Surface galled
Hangsterfer's Forging Compound Number 1	200	No galling. Lubricant adheres tenaciously to specimen
Spray Graph	125	Surface galled
Talc	700	Surface galled
Woven Asbestos	900	No specimen movement
Fisk Number 604	200	Surface galled. Lube Breaks down above 600°F
Boron Nitride	200	No galling. Specimen cleaned with tap water rinse.

c. Insulation Tests

A sub-scale test program was conducted to find a method of minimizing radiation losses from the part during the solution heat treat operation. A fused silica ceramic die was constructed to simulate the actual die with a channel section of .125-inch thick 7039 aluminum alloy simulating the part (Figure 35).

Holes were drilled in the part to permit temperature readings to be taken on both the die and part.

The insulation of batt type blankets of various thicknesses were tested (Figure 36) with results shown in Figure 37. A 3-1/2-inch thick blanket resulted in a maximum thermal gradient of 50°F between the die surface and the outer surface of the part (Figure 38). These findings resulted in the decision to fabricate a set of insulated doors to minimize radiation losses from the die.

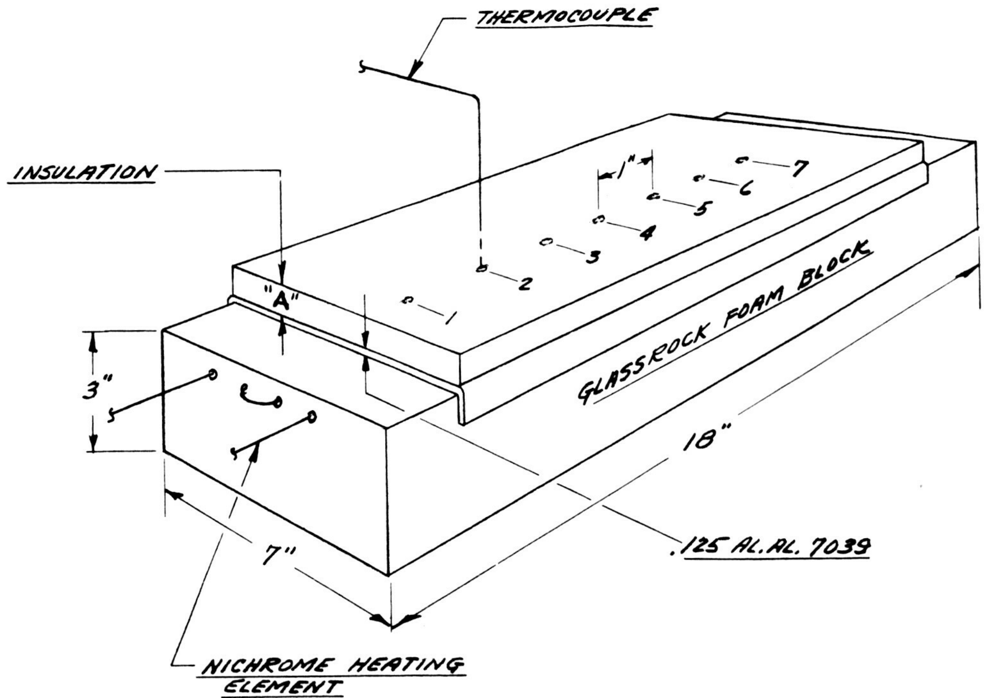


FIGURE 35. Insulation Test Setup

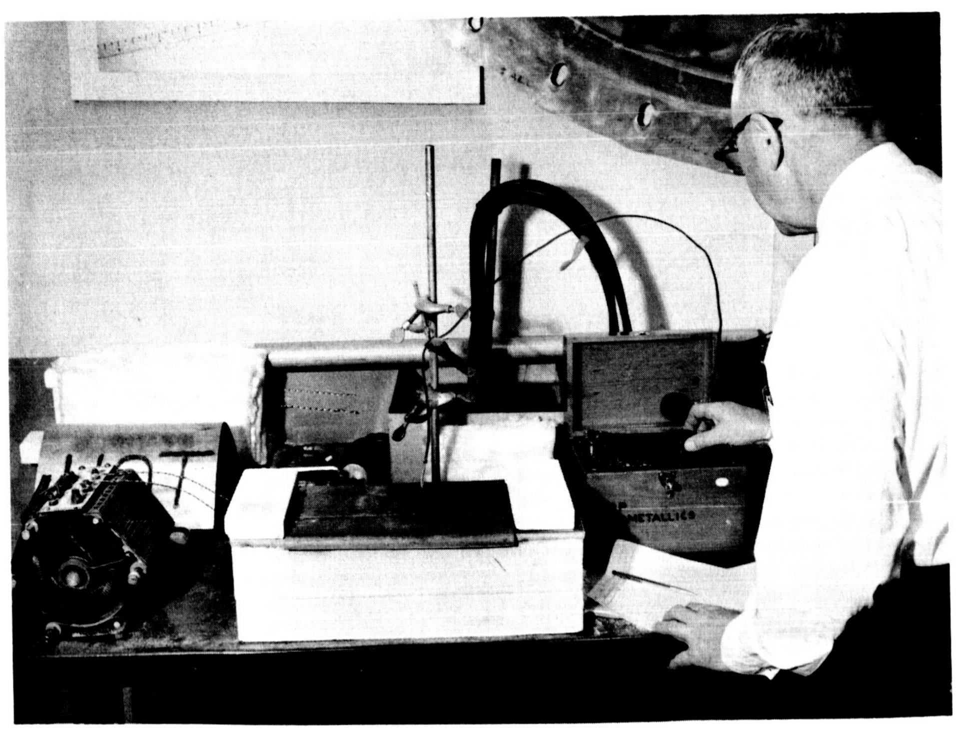


FIGURE 36. Insulation Test Setup MR3897

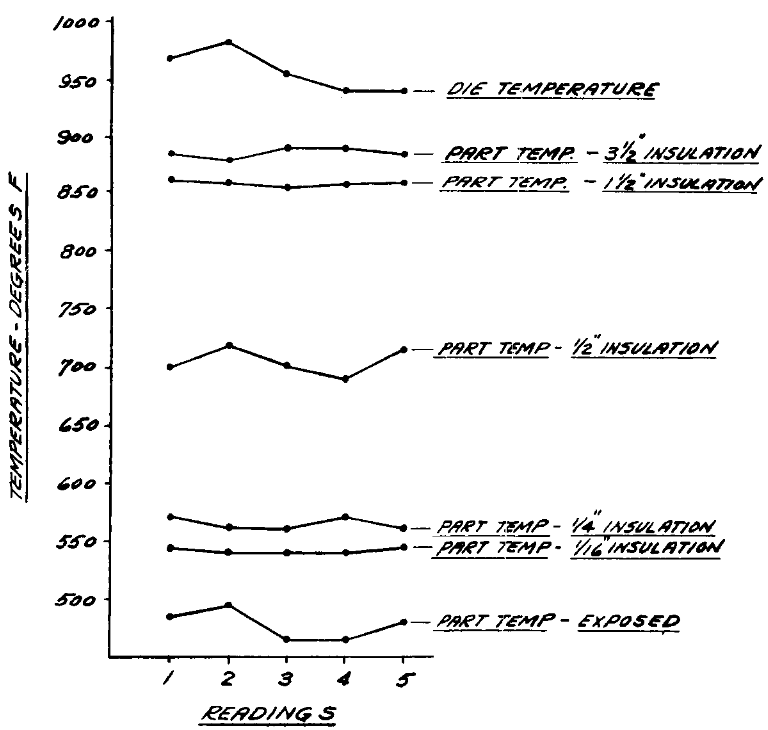


FIGURE 37. Insulation Test Result

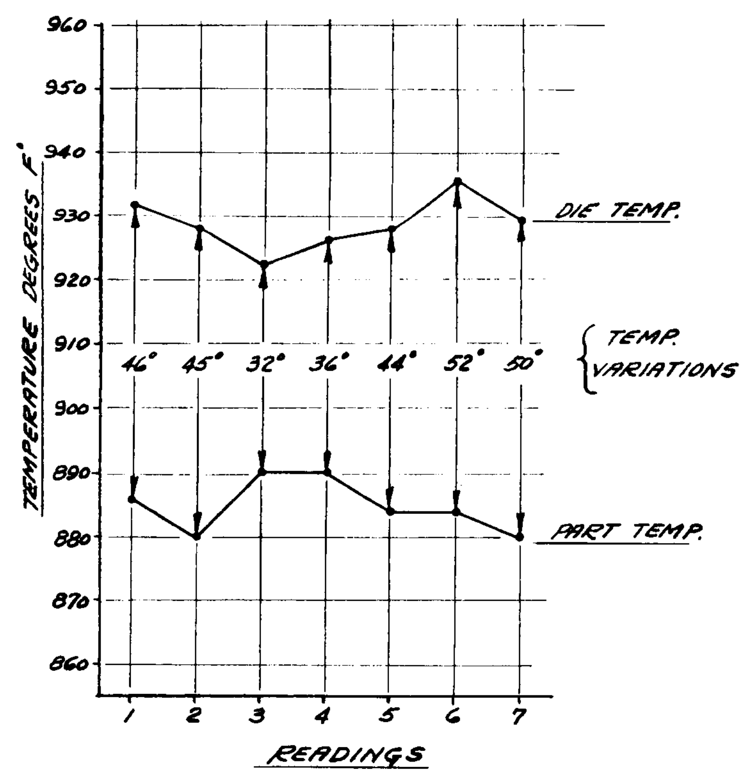


FIGURE 38. Insulation Test Result

2. PRODUCTION OF ALUMINUM PARTS

The first forming test was performed using a sheet of .032" thick (Type 321)stainless steel. This was to form a protective scuff sheet to be used to protect the die surface and to be permanently attached to the die face.

The sheet was cut to a length of 149". Nineteen two-inch diameter attach holes were blanked along each end and the sheet clamped in the gripping jaws. The die was heated to 850° F in approximately one hour. Hydraulic pressure to the actuating cylinders was set at 3500 psi which gave a calculated capacity of seventy tons while the tonnage required to form the skin was calculated to be forty-five tons.

The convex side of the part was stretched first and formed without a wrinkle. However, when the concave side was stretched considerable wrinkling occurred in that area (Figure 39). Further stretching to pull out the wrinkles was not possible due to the fact that the pistons had moved through their entire stroke.

Another effort to form a stainless steel scuff sheet was attempted. This time a shorter blank was used (147" instead of 149" on the first sheet) toensure that maximum stroke would be available in the hydraulic cylinders to attempt to stretch out the forming wrinkles.

The same sequence of operations was followed as with the first sheet with the convex side formed first followed by the concave side. The result was an improvement over the first trial but still unsatisfactory in that wrinkles were still in evidence at the completion of the forming operation. An effort to hammer out the wrinkles proved to be unsuccessful (Figure 40).

Due to the difficulty encountered in attempting to form this thin gage sheet and recognizing that a higher degree of temperature uniformity would be realized if the number of interfaces between the heat source and the workpiece were kept to a minimum, it was decided to eliminate the scuff sheet entirely. In its place, die lubricants to protect the die surface and prevent galling of the part were considered. The series of tests previously described were conducted and boron nitride was chosen as the most suitable lubricant for this application.

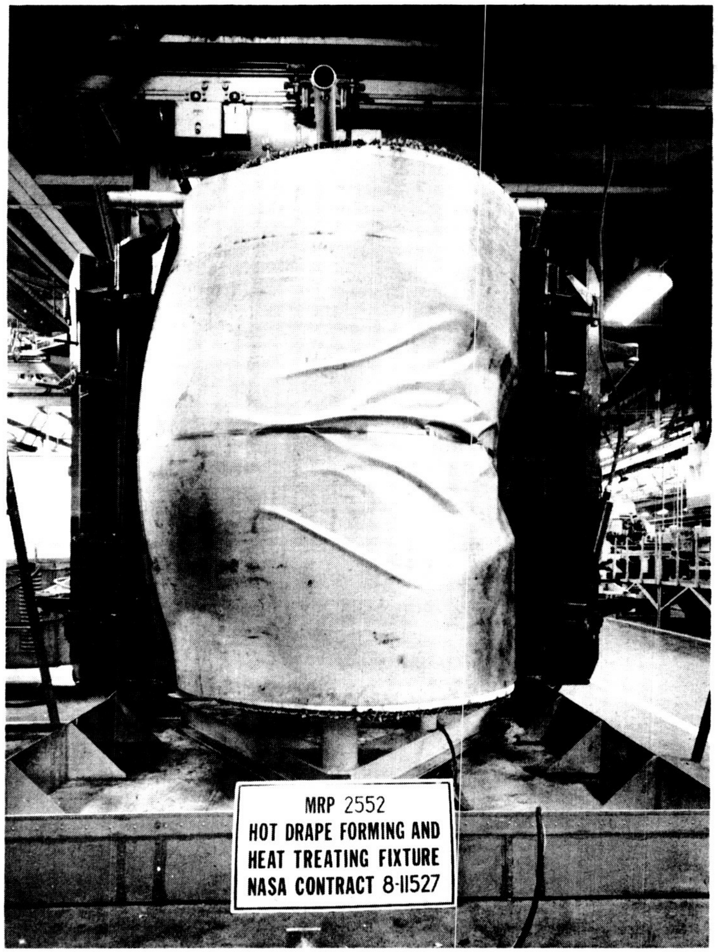


FIGURE 39. First Scuff Sheet MR3724

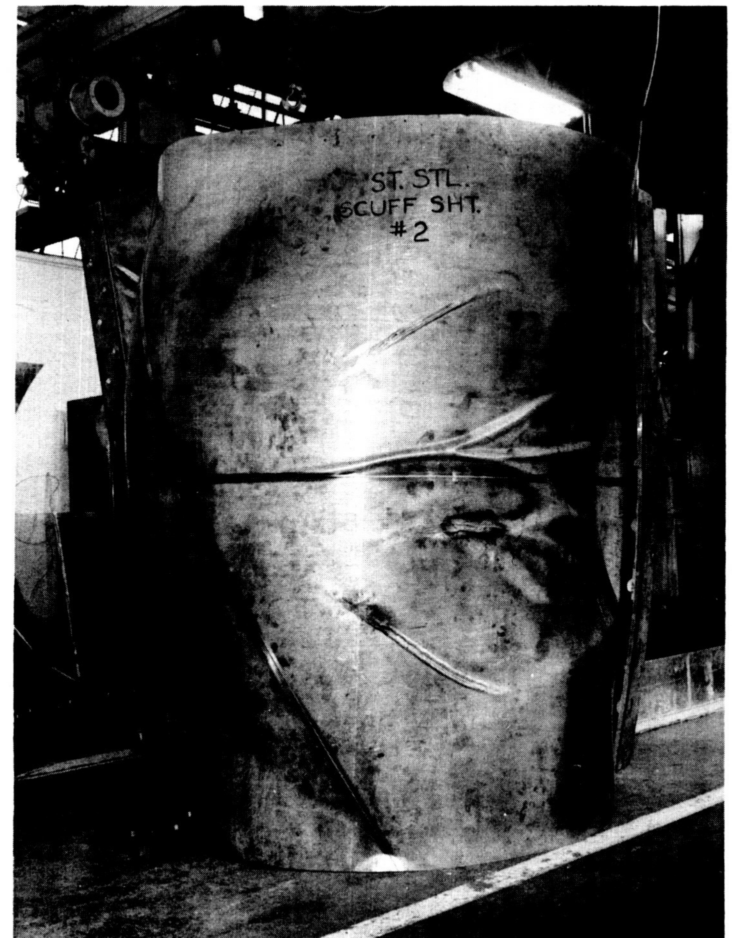


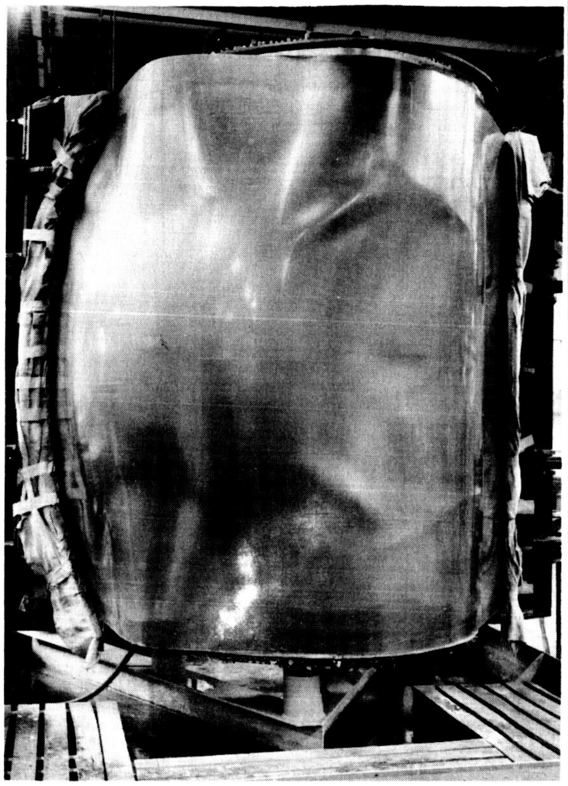
FIGURE 40. Second Scuff Sheet MR3855

a. Part Number 1 - Part blanks of 7039 aluminum alloy . 125" x 90" x 160" in the "W" plus at least three months' natural age condition were furnished by MSFC. Since shortened blanks were found necessary as a result of forming the scuff sheets, a part blank was prepared 147" long for preliminary forming tests. Mounting holes were blanked in the ends and the part then roll formed to a "U" shape to facilitate loading in the jaws (Figure 41, upper left). The die temperature was set to 850°F in all zones.

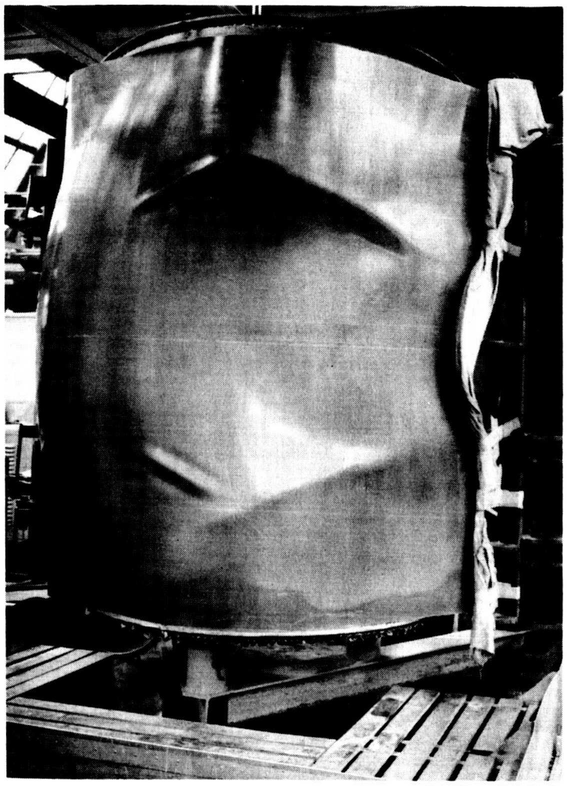
The wiper plate mechanism on the convex side (Zones 1, 2, 3) was actuated and forming began in that area. However, excessive orange-peel and thinout occurred, resulting in a 12" long transverse crack on the convex side. In an effort to complete forming of the concave side of the part, the three heat zones (1, 2, 3) in the convex area were turned off and the three heat zones (4, 5, 6) in the concave area were left at 850°F. The wiper plate in the concave area was actuated and the remainder of the part formed without a wrinkle. After careful examination of the part, it was felt that the 850°F left the part too weak and ductile to withstand the forming operation and it was decided to reduce forming temperatures. It was also noted that the part stretched more in zone 5 than in either zone 4 or 6, indicating a higher temperature in that zone. Figure 41 shows the drape form operation in different stages of forming. An overall view of the operation shows quench hood (quench shield) at left, completed part in the center and heating controls at the right (Figure 42).

Prior to the forming of any more parts, a colloidal solution of boron nitride in water was applied to the surface of the die in the area common to the trimmed part only. It was reasoned that the omission of the lubricant from the portion of the die outside the trim of the part and the residual difference in coefficient of friction would tend to minimize the transverse movement of the sheet into the concave area and thus lessen the tendency to form wrinkles. The lubricant was applied by rubbing one heavy coat into the surface followed by two light spray coats. The die was then slowly heated to dry out on the boron nitride.

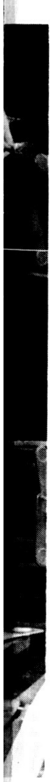
R 4323

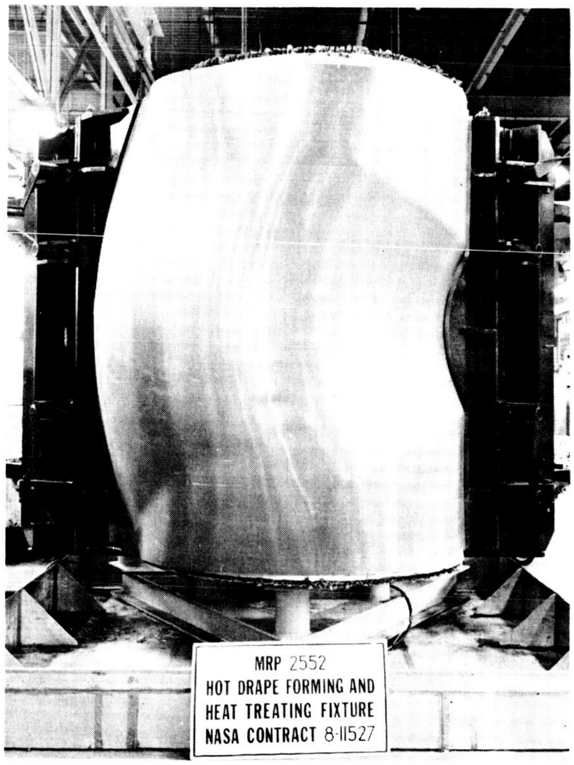


MR 4322

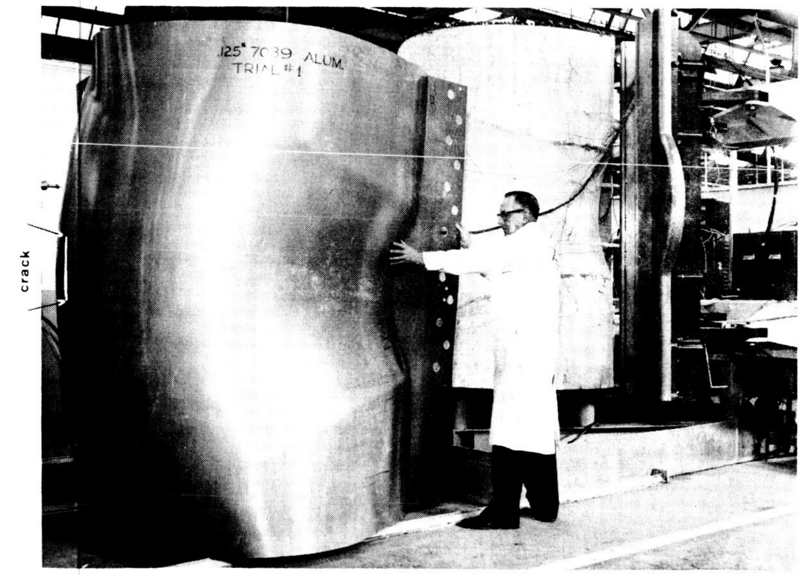


MR 4320





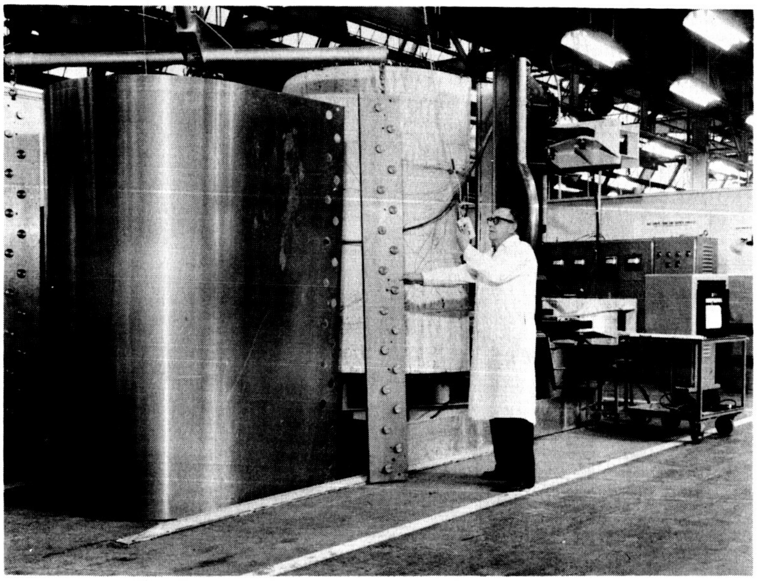
MR 3836



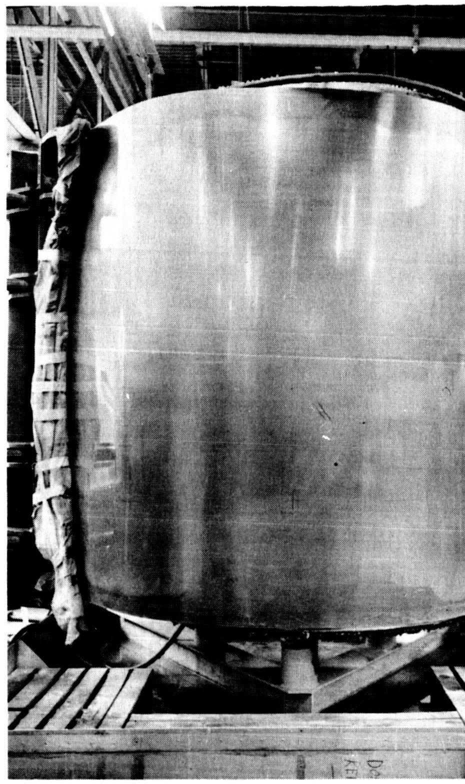
MR 3857

43-2

FIGURE 41. Series of Forming Stages for Trial No. 1



MR 3856



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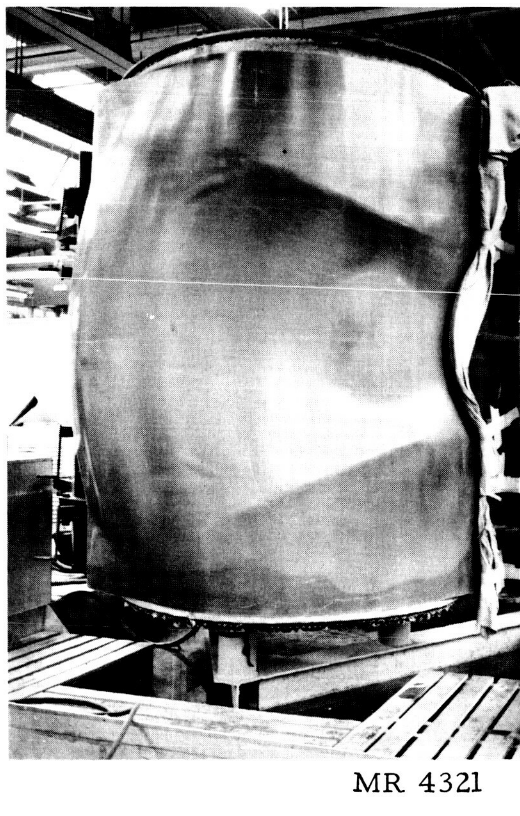


MR 4321

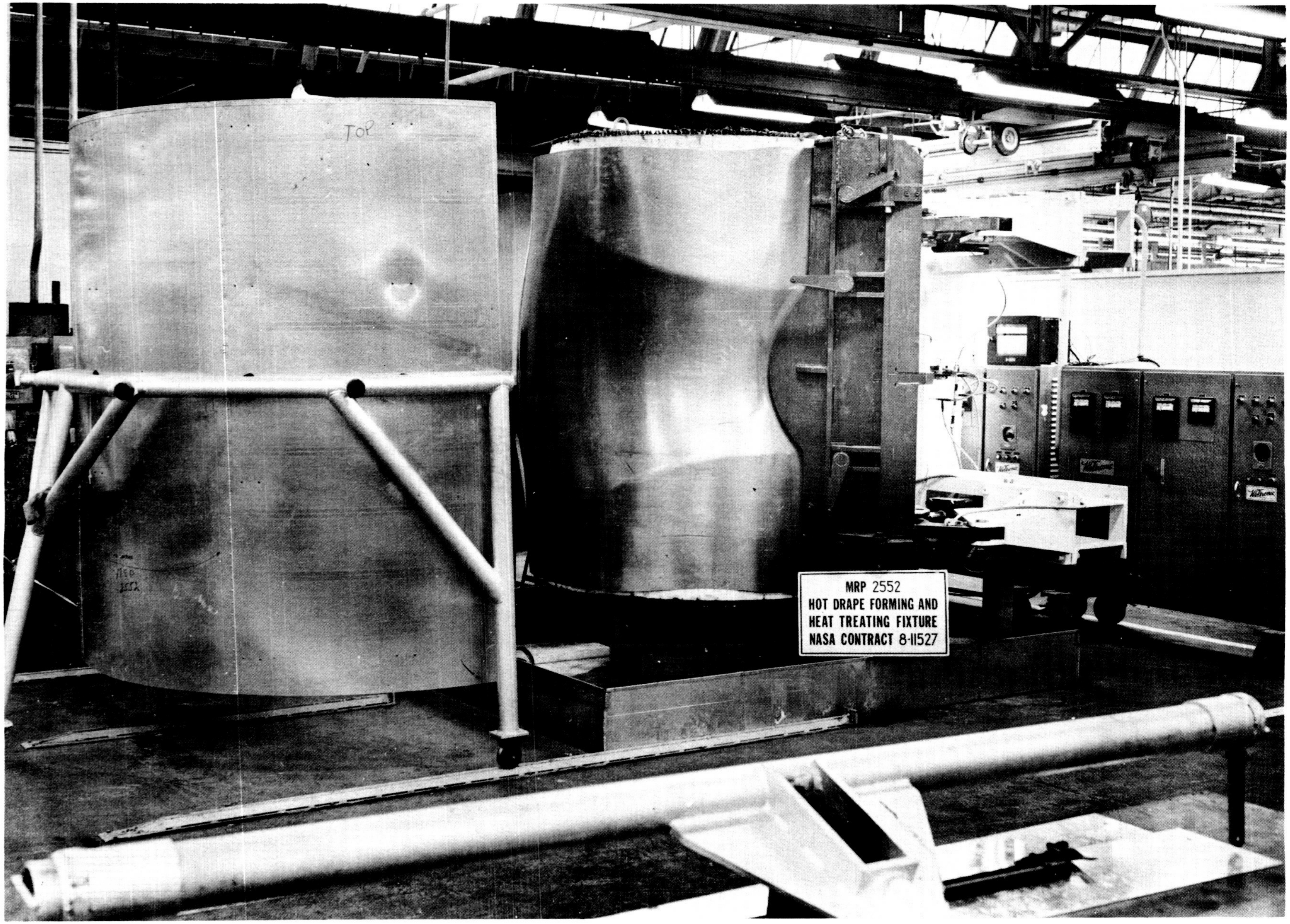


FIGURE 42. Overall View of the Operation. Quench Shield at Left, Formed Part in Center on Die and Heating Controls at the Right MR 3837

b. <u>Part Number 2</u> - Part No. 2, 147" long was prepared with a grid pattern of 12" squares marked over the entire surface and mounted on the lubricated die. For this part, the die temperature was set at 500°F in all zones. As the drape forming operation progressed, temperature readings were taken in each zone and recorded. A chart was made of the temperature contour lines on the part as it was formed versus stroke contour lines on the part as it was formed versus stroke position of the jaws (Figure 43). In addition, readings were taken of transverse and longitudinal dimensional changes in the size of the 12" grid to determine maximum stretch areas in an effort to maintain uniformity in material thickness. Sheet thickness readings by vidigage were also taken with results shown in Figure 44.

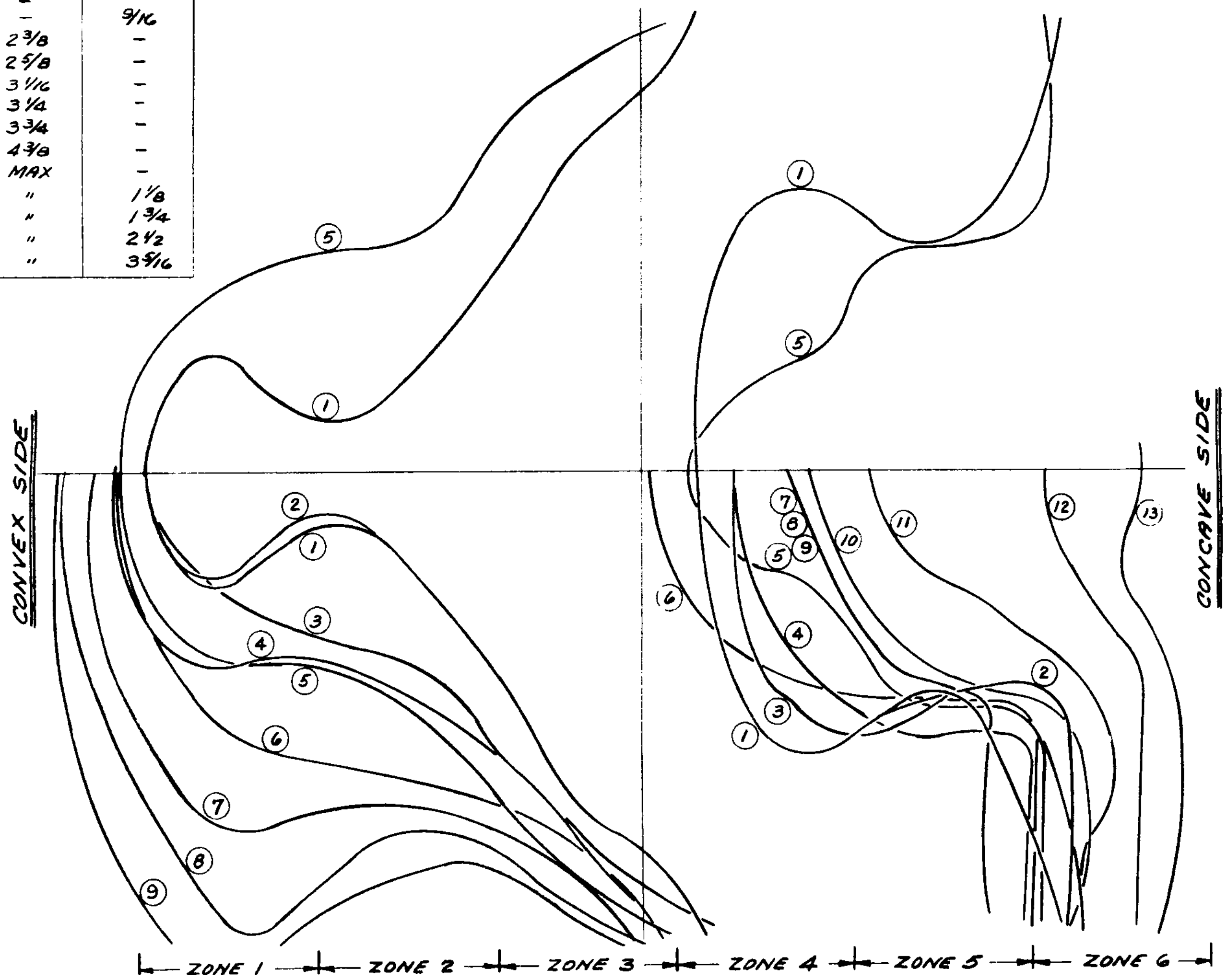
The jaw was actuated in equal increments to form the convex area of the part until it stalled at a set pressure of 3500 psi. At this point, the temperature was raised in all zones to 600°F to decrease the yield strength of the material. The jaw was again actuated until the wiper plate homed on the die. The temperature in the formed convex area (zones 1, 2, 3) was then dropped to 500°F to minimize additional stretch in that area (see temperature-zone record in inset below). The jaw in the concave area was then actuated until the wiper plate homed on the die.

ZONE	1	2	3	4	5	6	Zone 1 2 3 4 5 6
Initial Temp.	500	500	500	500	500	500	500°F
Change 1	600	600	600	600	600	600	600°F
Change 2	500	500	500	600	600	600	600°F 500°F

PART NUMBER 2

Changes in Heat Pattern During Forming Operation

STROKE	CONVEX	CONCAVE
1	2"	–
2	–	9/16
3	2 3/8	–
4	2 5/8	–
5	3 1/16	–
6	3 1/4	–
7	3 3/4	–
8	4 3/8	–
9	MAX	–
10	"	1 1/8
11	"	1 3/4
12	"	2 1/2
13	"	3 5/16



NOTE:

1- TEMPERATURE SETTING 500°F.

2- 400°F. TEMPIL STICK APPLIED TO DETERMINE AREA AT 400°F AND HIGHER TEMPERATURES

FIGURE 43. Heat Pattern Composite Part No. 2

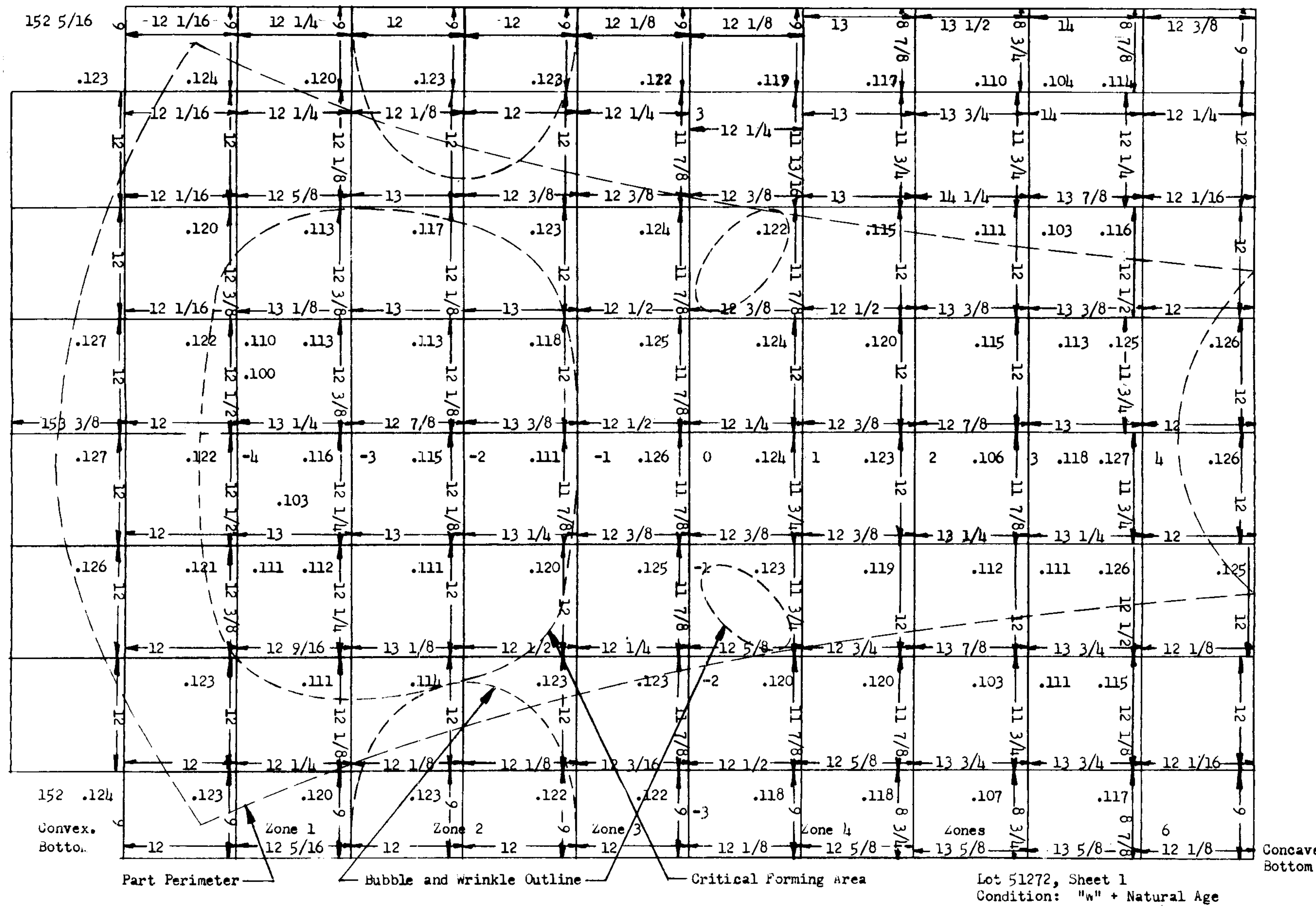


FIGURE 44. Part No. 2 Stretch Pattern (Horizontal and Vertical) Material Thickness *hot dimension

This part formed without wrinkles, but there were two areas on the top and bottom edge that did not wipe out to clear the actual trim of the part. It was decided that shortening the length of the blank would solve this problem.

Upon completion of Part No. 2, a heat survey was run on the die in preparation for solution heat treat and artificial aging operations. Heat survey tests were conducted on the die at two temperatures - 320°F and at 850°F. This generally covered the two operating ranges used for aging and for solution heat treating respectively. Tests were conducted using twenty-four chromel-alumel thermocouples (four thermocouples located in each of the six heating zones) attached to a recorder. The thermocouples were attached to the die surface with asbestos web straps.

In actual tests, a stable and uniform temperature of 320°F was recorded in all zones on the open die surface. However, the open die was not able to reach the set temperature of 850°F at full power due to large radiation losses. The maximum temperature reached after four hours heat-up time was 780°F. Nevertheless, the die surface at this temperature was found to be uniform in all zones.

A formed part (Part No. 2) was then remounted on the die and used in the second phase of the heat survey tests. Twenty-four thermocouples were bolted to the outer surface of the part. The die was heated to 320°F and stabilized in half an hour. Thermocouple readings indicated that at this temperature, a tolerance of $\pm$ 10°F can be achieved. Cooling and reheating of the die showed that this temperature and tolerances were repeatable. With the formed part still on the die, the temperature was raised to 850°F in about one hour from room temperature. Due to large radiation losses, readings indicated that temperature uniformity in a zone varied by as much as 115°F. A thermal gradient of 80°F was observed through the thickness of the sheet.

Separate sub-scale tests had indicated that the use of insulation would remedy this condition. It was decided to build two swinging insulated doors to be used during the solution heat treat cycle (Figure 45). These doors were instrumental in limiting the temperature variation throughout the die to $\pm$40° at 850° .

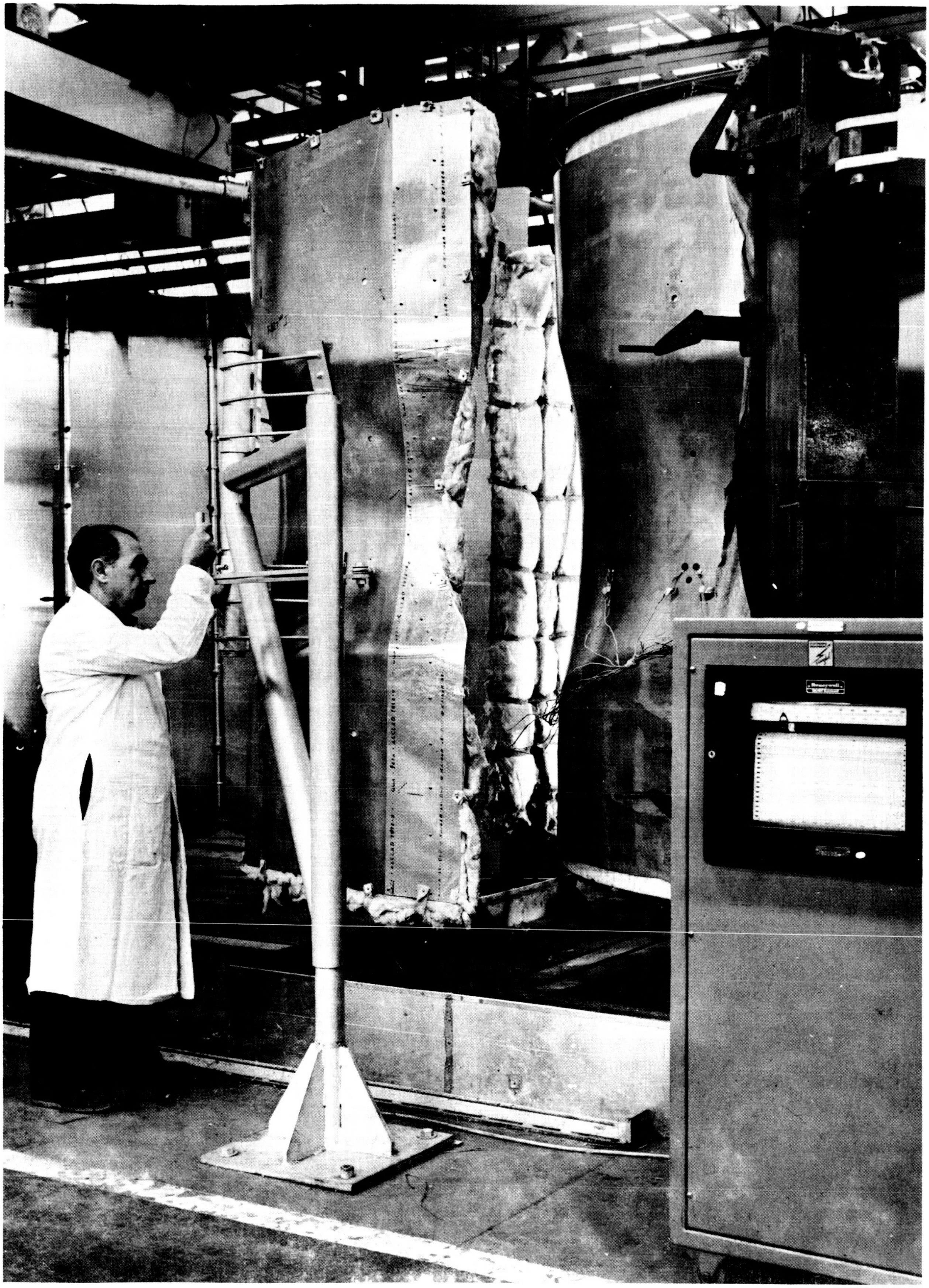


FIGURE 45. Insulated Doors being Swung into Position MR4041

At the completion of the heat survey, the spray quench rate and system was checked out with the part at 850° F. Thermocouples were inserted between the formed aluminum sheet and the die surface through holes in the part and connected to a recorder. Tension on the part was relieved and the power to the heating elements turned off. The spray quench hood was rolled into position and the water spray applied to the part for a period of forty seconds.

The part was backed off to clear the die, and coolant water from a pipe along the top of the die was flushed against the die surface to prevent the temperature from rising due to conduction from residual heat in the interior of the die (see Figure 46).

The recorder indicated that the die surface reached room temperature in 6-8 seconds at maximum rate of water flow.

c. Part Number 3 - Part No. 3, 146" long, was prepared with a grid pattern and mounted on the hot drape fixture. All zones of the die were initially heated to 600° F and forming started in the convex area. As the forming progressed, it was noted that the area in zone number 1 was stretching too rapidly relative to zones 2 and 3. The temperature in zone 1 was reduced to 300° F. Forming was continued until cracking occurred in some of the mounting holes adjacent to zone 1. That jaw was locked in position and forming started on the concave side. After forming part way, the temperature was changed to 650° F in zone 4 and to 550° F in zone 5 in an effort to remove two center wrinkles and the side bubbles on the upper and lower edge (see temperature-zone record in inset below).

ZONE	1	2	3	4	5	6	Zone 1 2 3 4 5 6
Initial Temp.	600	600	600	600	600	600	600° F
Change 1	300	600	600	600	600	600	600° F 300° F
Change 2	300	600	600	650	550	600	600° F 300° F

PART NUMBER 3-Changes in Heat Pattern During the Forming Operation

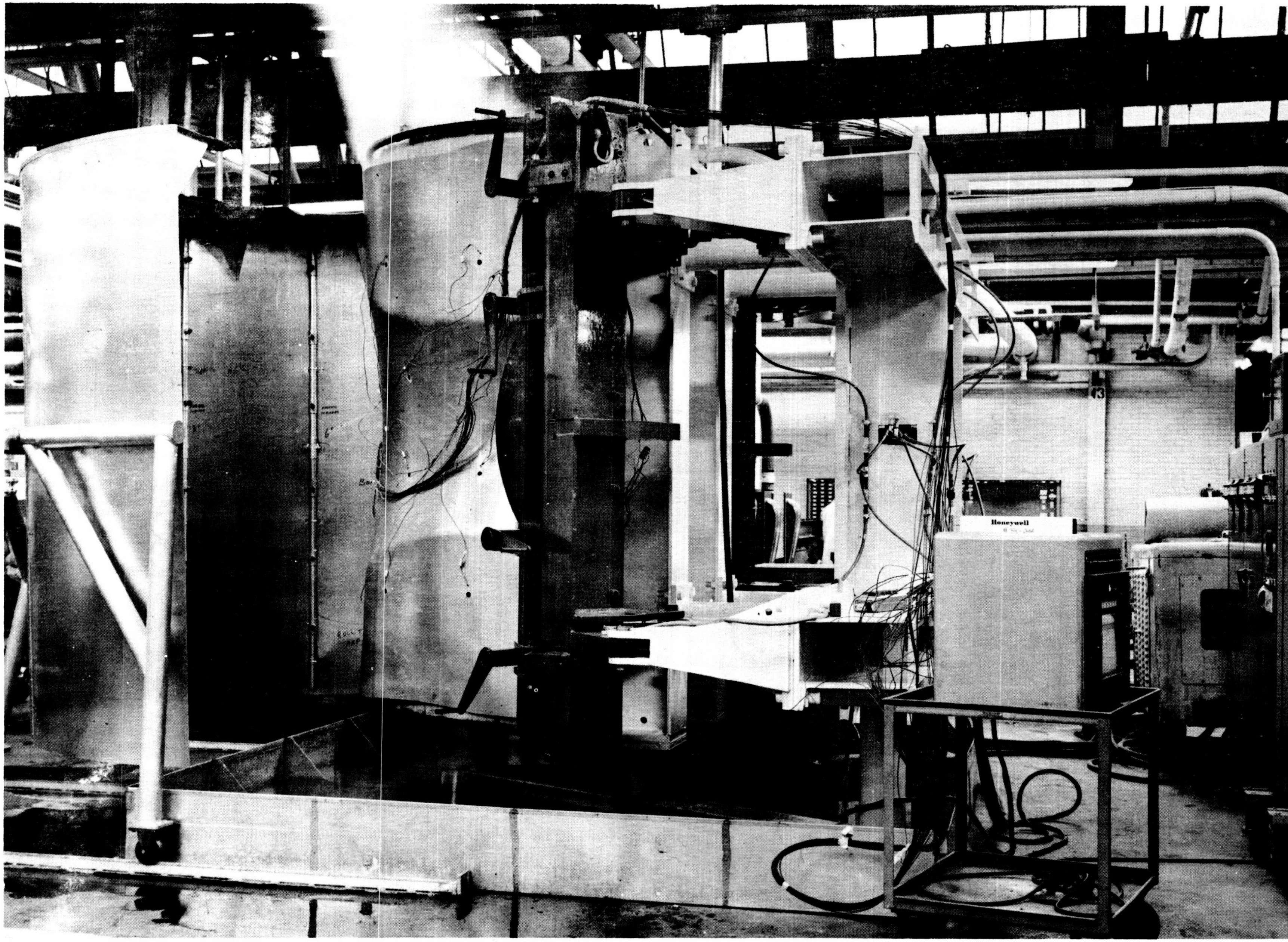


FIGURE 46. Water Mist Rising from Hot Die after Quenching and Part Retraction MR3870

Due to the cracking along the mounting holes, it was not possible to move the bubbles on the upper and lower edge out past the final trim of the part by stretching, missing it by 1-1/2". However, the bubble was removed by hand working while still on the die to produce an acceptable test part.

During the forming operation, temperature readings were taken to develop a heat pattern (Figure 47). Upon completion of forming, the amount of stretch in the grid pattern and the sheet thickness were measured and recorded (Figure 48).

d. Part Number 4 - Parts 1, 2, and 3 were all formed in the as-received "W" plus natural age condition. It was decided to try an annealed sheet to determine the effect on forming characteristics.

Part Number 4 was annealed at 750° F for one hour and cooled at 100° F/hour followed by four hours at 450° F. The blank, 146" long, was prepared and loaded on the die. In an effort to equalize the stretch and minimize material thinout, the die temperature was varied as forming progressed as indicated in the inset below:

ZONE	1	2	3	4	5	6	Zone 1 2 3 4 5 6
Initial Temp.	600	650	550	600	600	600	
Change 1	600	650	600	600	600	600	
Change 2	600	600	650	600	600	600	
Change 3	550	600	650	600	600	600	
Change 4	550	600	700	600	600	600	
Change 5	550	600	700	650	600	600	
Change 6	550	600	700	700	600	600	
Change 7	500	600	700	700	600	600	
Change 8	500	600	650	700	600	600	
Change 9	500	600	650	650	600	600	

PART NUMBER 4

Changes in Heat Pattern During the Forming Operations

STROKE	CONVEX	CONCAVE
2	1 5/16"	–
3	2"	–
4	2 1/2"	–
5	3 3/8	–
6	–	2
7	3 7/8	–
8	3 7/8	–
9	–	2 1/2
10	–	3
11	–	3 1/4
12	–	3 1/2

NOTE:

1- TEMPERATURE SETTING 600°F.

2- 400°F. TEMPIL STICK APPLIED TO DETERMINE AREA AT 400°F. AND HIGHER TEMPERATURES

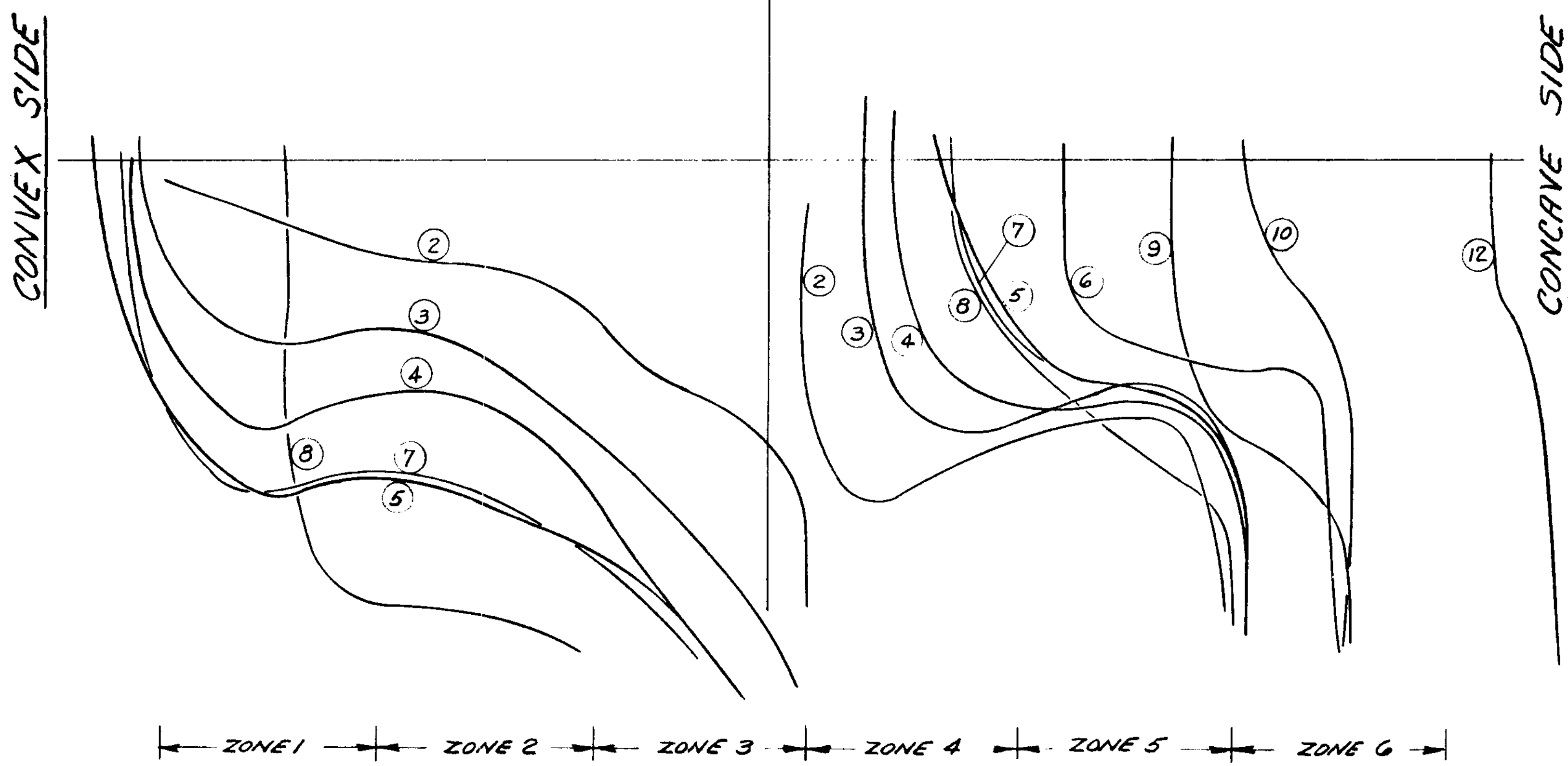


FIGURE 47. Heat Pattern Composite - Part Number 3

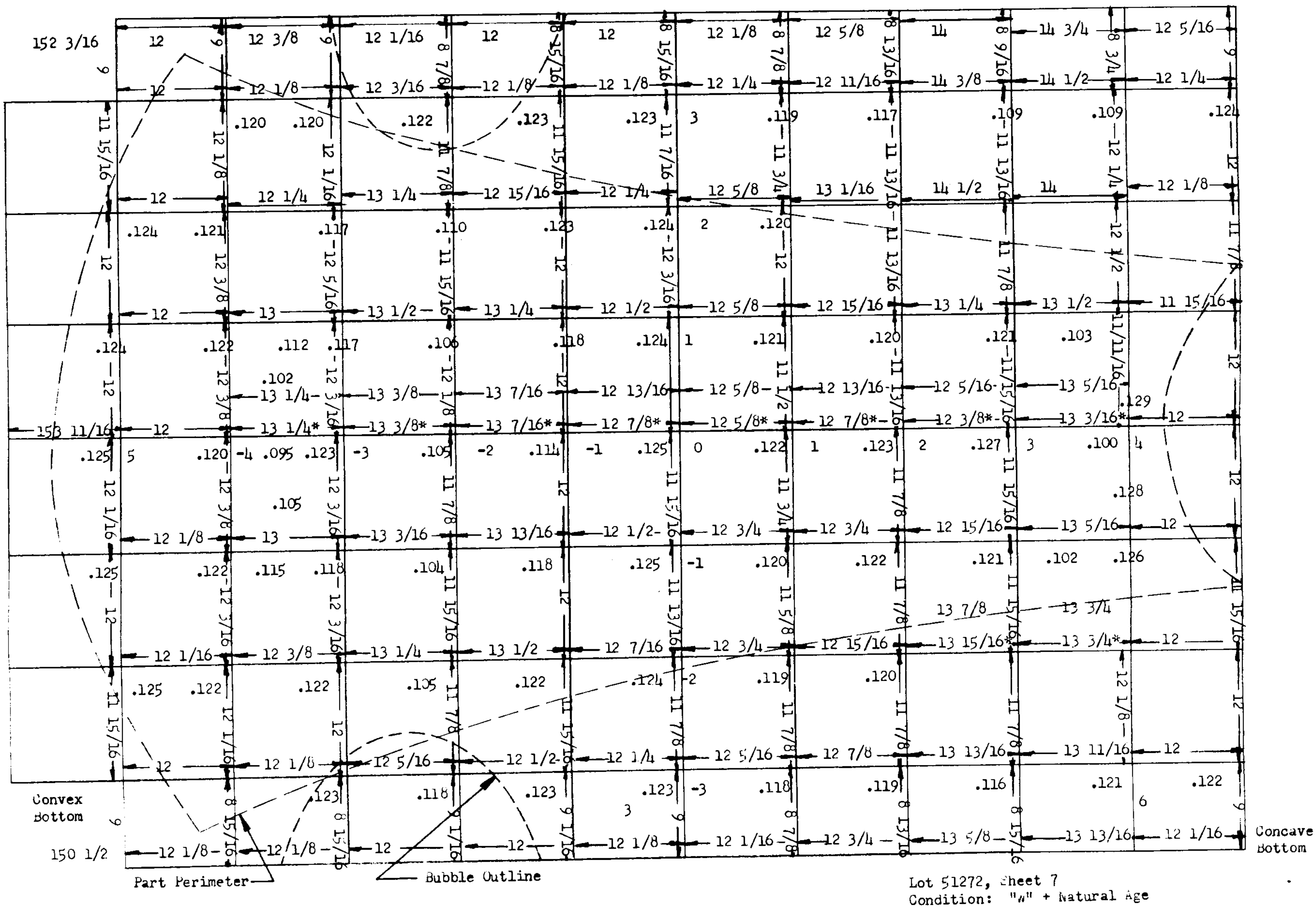


FIGURE 48. Part No. 3 Stretch Pattern (Horizontal and Vertical) Material Thickness (*hot dimension)

As with the preceding parts, drape forming was started in the convex area. After completion of forming in that area, the concave area was formed. This part was completely formed with the bubble on the top and bottom edge moved out 1" past final trim line.

Readings of stretch in the grid pattern and vidigage readings of the sheet thickness (Figure 49) showed an improvement over the preceding parts. In addition, the surface appearance was improved with less evidence of orange peel. As a result, all of the remaining parts were annealed and formed in this condition.

e. <u>Part Number 5</u> - Part Number 5 was formed from an annealed blank in the same manner as Part No. 4, except that the initial temperature in Zone 3 was raised 100°F to attempt to move the bubble further outside the final trim line. Measurements of the stretch pattern were again recorded in addition to vidigage readings of sheet thickness (Figure 50). While the part was formed with the bubble 3" past final trim, the material thickness in the convex area was reduced in one area to .097" from the original gauge of .125".

Die temperatures were varied during the drape forming operation as shown in the inset below:

ZONE	1	2	3	4	5	6	Zone 1 2 3 4 5 6
Initial Temp.	600	650	650	600	600	600	
Change 1	550	600	700	700	600	600	
Change 2	500	600	700	700	600	600	
Change 3	500	600	700	700	550	600	
Change 4	500	600	700	700	550	650	
Change 5	500	550	700	700	550	700	
Change 6	500	500	500	500	500	700	

PART NUMBER 5

Changes in Heat Pattern During Forming Operations

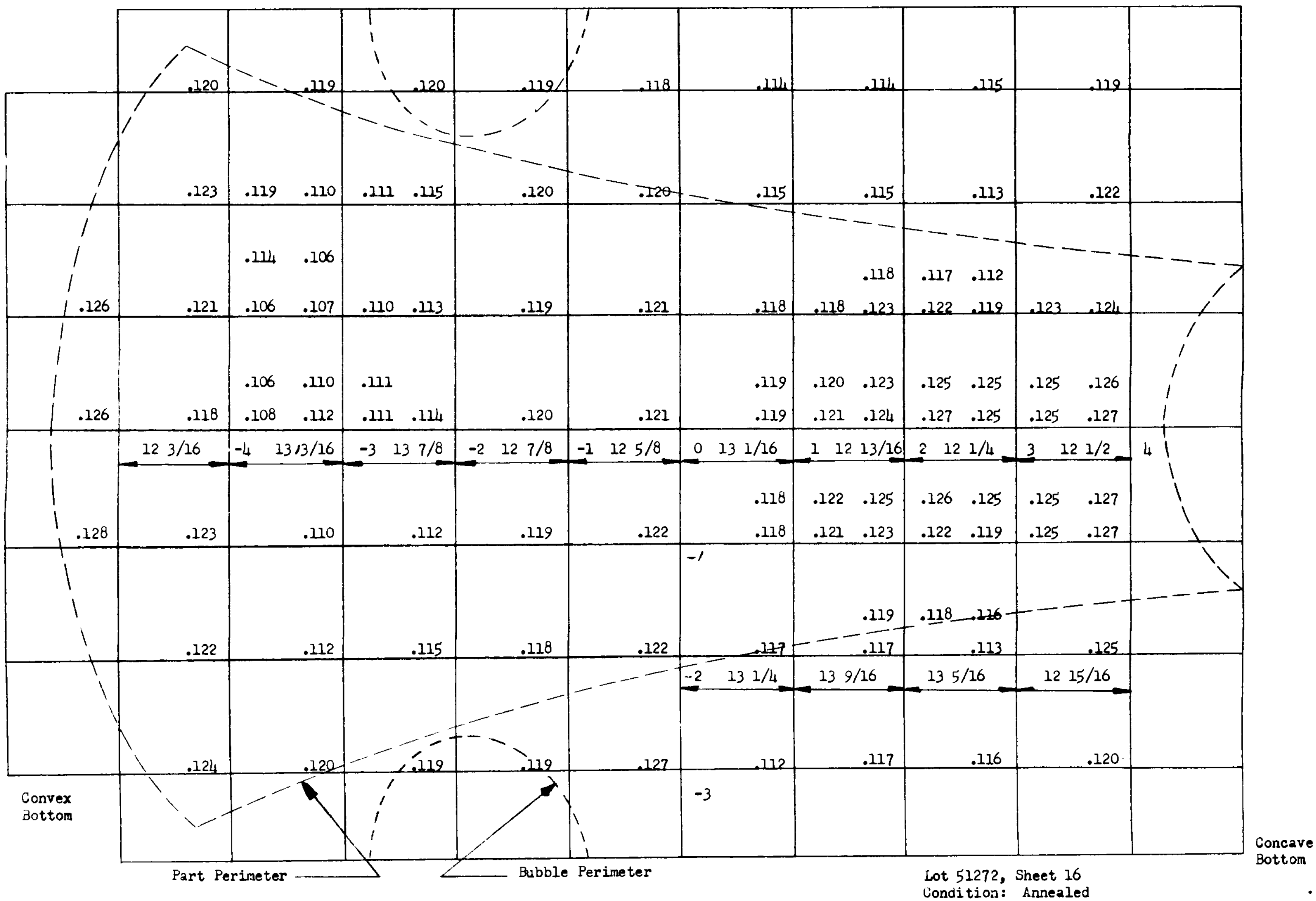


FIGURE 49. Stretch Pattern Material Thickness - Part No. 4

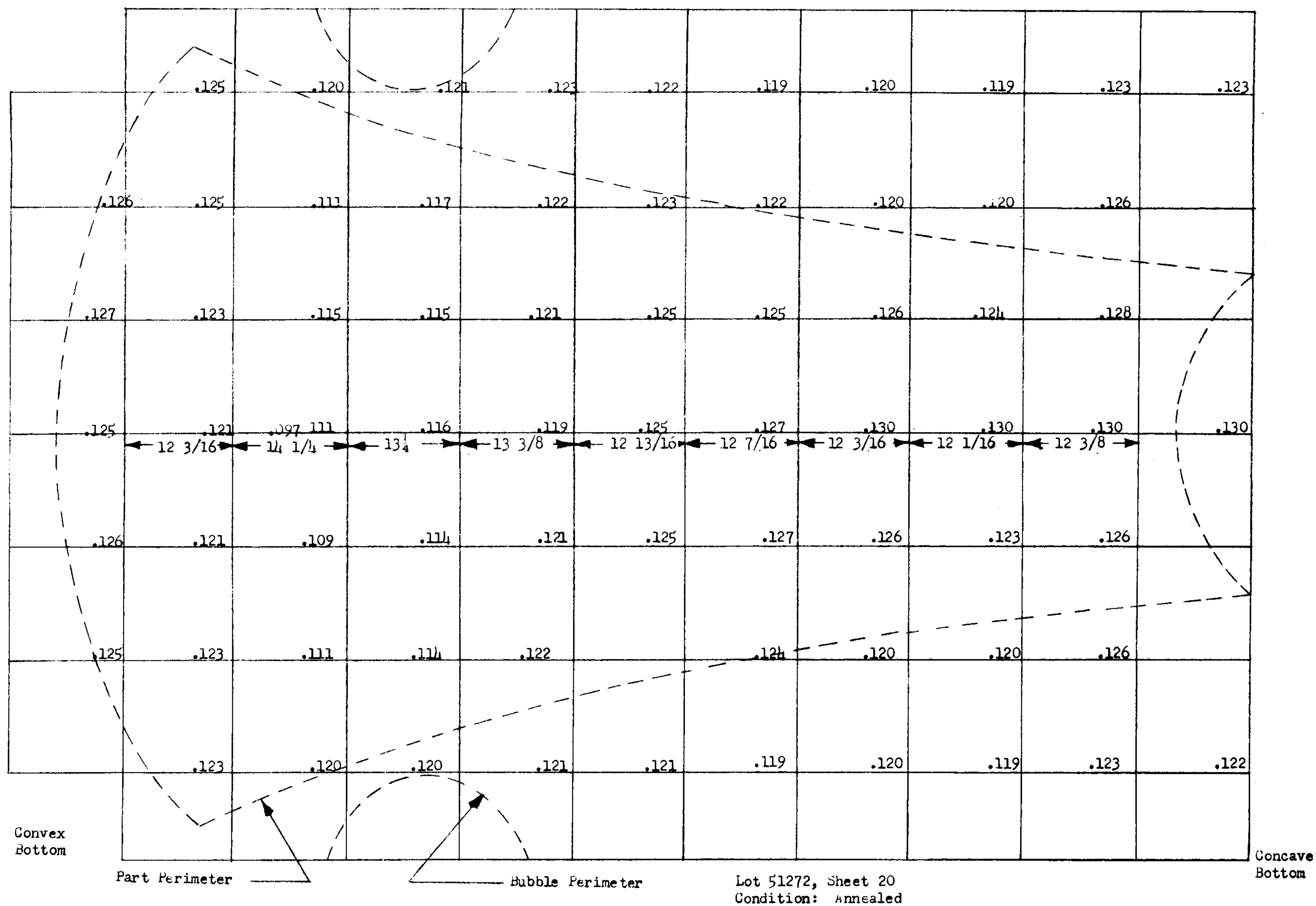
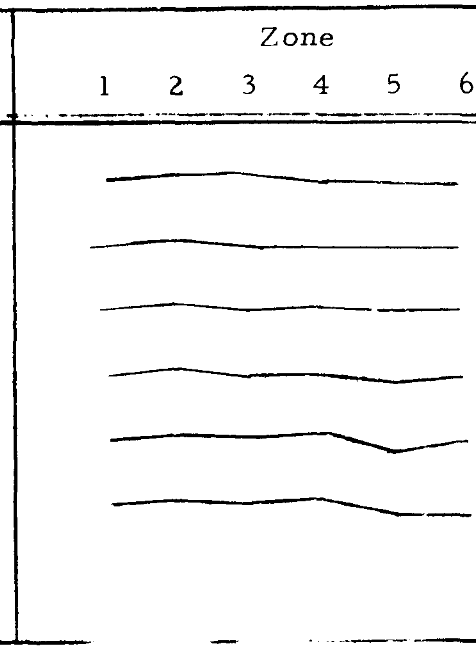


FIGURE 50. Stretch Pattern Material Thickness - Part No. 5

f. Part Number 6 - This part was designated as a heat treat qualification test part to be destructively tested by the removal of specimens from all areas for tensile testing.

The test sheet was prepared with a marked grid pattern as on previous parts and mounted in the jaws. The die was brought up to the temperature range and forming started on the convex side. Upon completion of the convex side, the concave side was formed. The initial temperature in all zones and the changes made in the different zones as forming progressed, are shown in the insert below.

ZONE	1	2	3	4	5	6
Initial Temp.	600	650	650	600	600	600
Change 1	600	650	600	600	600	600
Change 2	600	650	600	620	600	600
Change 3	600	650	600	620	550	600
Change 4	600	650	630	650	550	600
Change 5	600	650	630	660	550	550



PART NUMBER 6

Changes in Heat Pattern During the Forming Operations

The formed part was then fitted with twenty-two thermocouples bolted to the surface. The insulated doors were swung into position and the die temperature was increased to the solution heat treat range and held at that temperature for the prescribed amount of time. Then the doors were swung out of the way, the tension relieved in the jaws and the power turned off. The spray hood was rolled into position and the part quenched. Upon completion, the part was removed and stored to permit natural aging. Following the natural age, this part was again mounted on the die for the artificial aging cycle.

Readings were taken of the changes in the 12" grid pattern and are shown in Figure 51. The temperature readings taken on the twenty-two thermocouples attached to the part plus two spring loaded thermocouples mounted on the insulated doors (#23, #24) are shown in Figure 52.

Upon completion of the aging cycle, the part was cut up to provide twenty-one test coupons for tensile tests (Figure 53). The results are shown in Figure 54.

The results of the qualification test and a "Procedure for Processing 7039 Aluminum Alloy Hot Drape Formed Parts was submitted to NASA for approval.

Upon approval of the test results and the forming procedure, the remainder of the torus segments were formed and heat treated. All parts were marked with a 12" grid pattern as a visual aid in forming to control stretch and resultant thinout. The die temperature in each of the zones was varied during forming to minimize thinout by monitoring the grid pattern. Figure 55 shows the final dimensions of the 12" grid for the remaining formed torus segments.

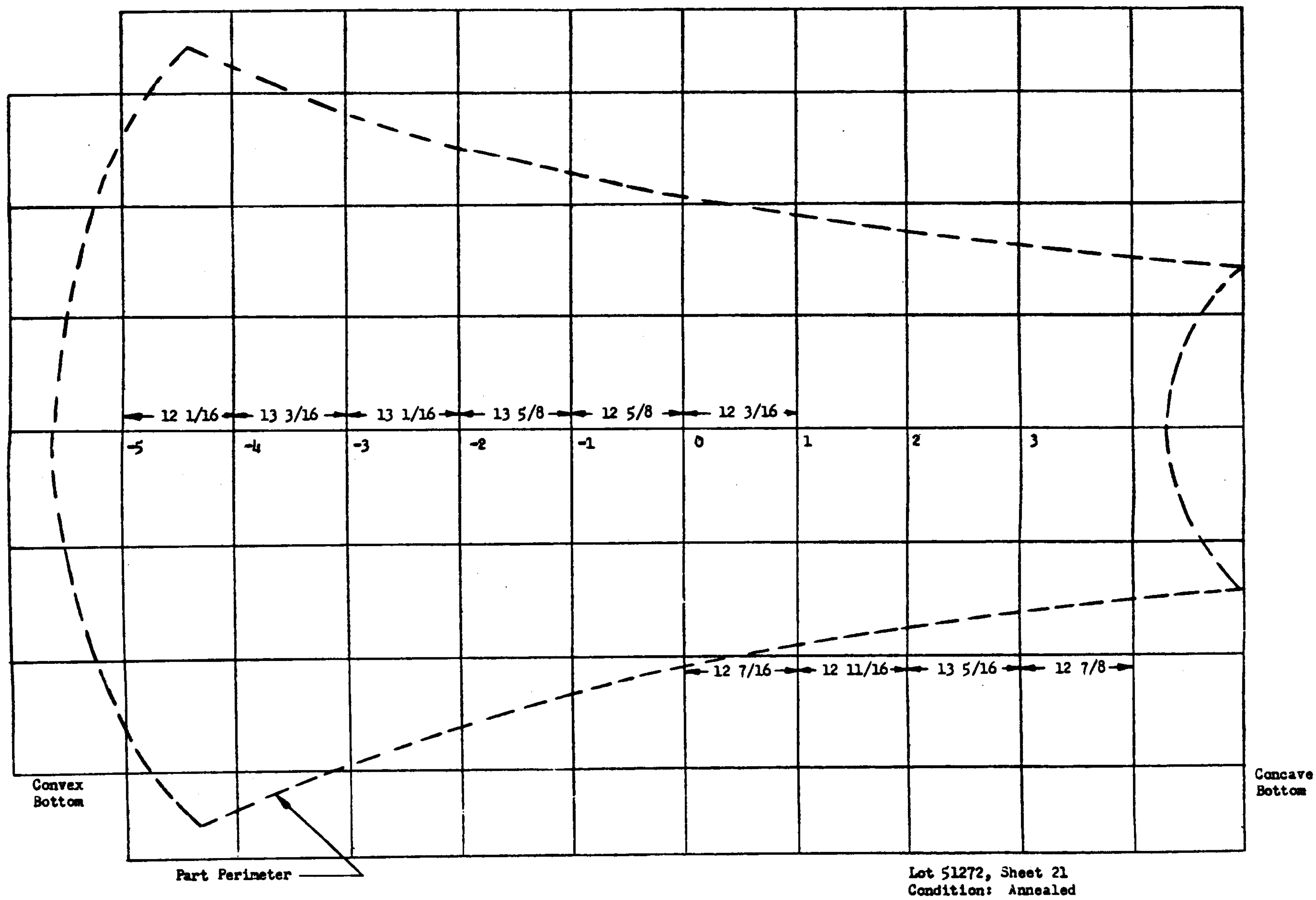
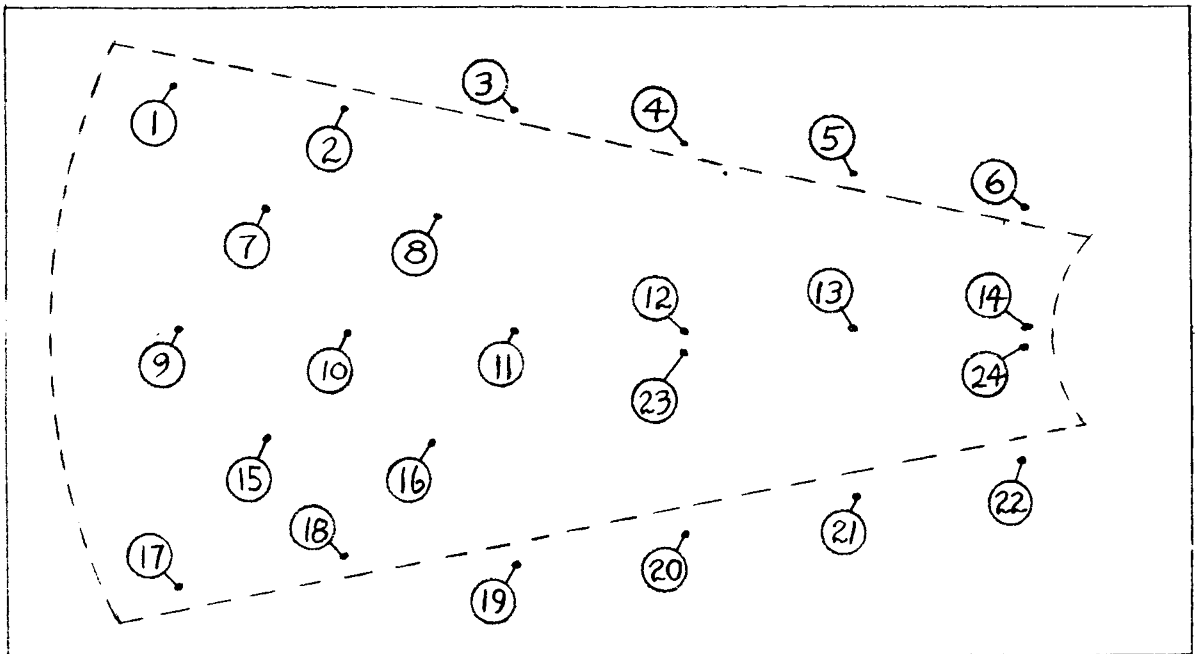


FIGURE 51. Stretch Pattern Qualification Test - Part No. 6



Location	Part Temperature, °F		
	Solution Treat	1st Age Cycle	2nd Age Cycle
1	775	210	300
2	795	210	300
3	843	210	300
4	857	210	300
5	872	210	300
6	872	210	300
7	900	210	300
8	885	210	300
9	885	210	300
10	885	210	300
11	825	210	300
12	840	210	300
13	863	210	300
14	810	205	283
15	882	210	300
16	815	210	300
17	775	210	300
18	775	210	300
19	675	210	300
20	815	210	300
21	852	210	300
22	855	210	300
23	850	-	-
24	812	-	-

FIGURE 52. Lot 51272, Sheet 21
Heat Treat Qualification Test - Part No. 6

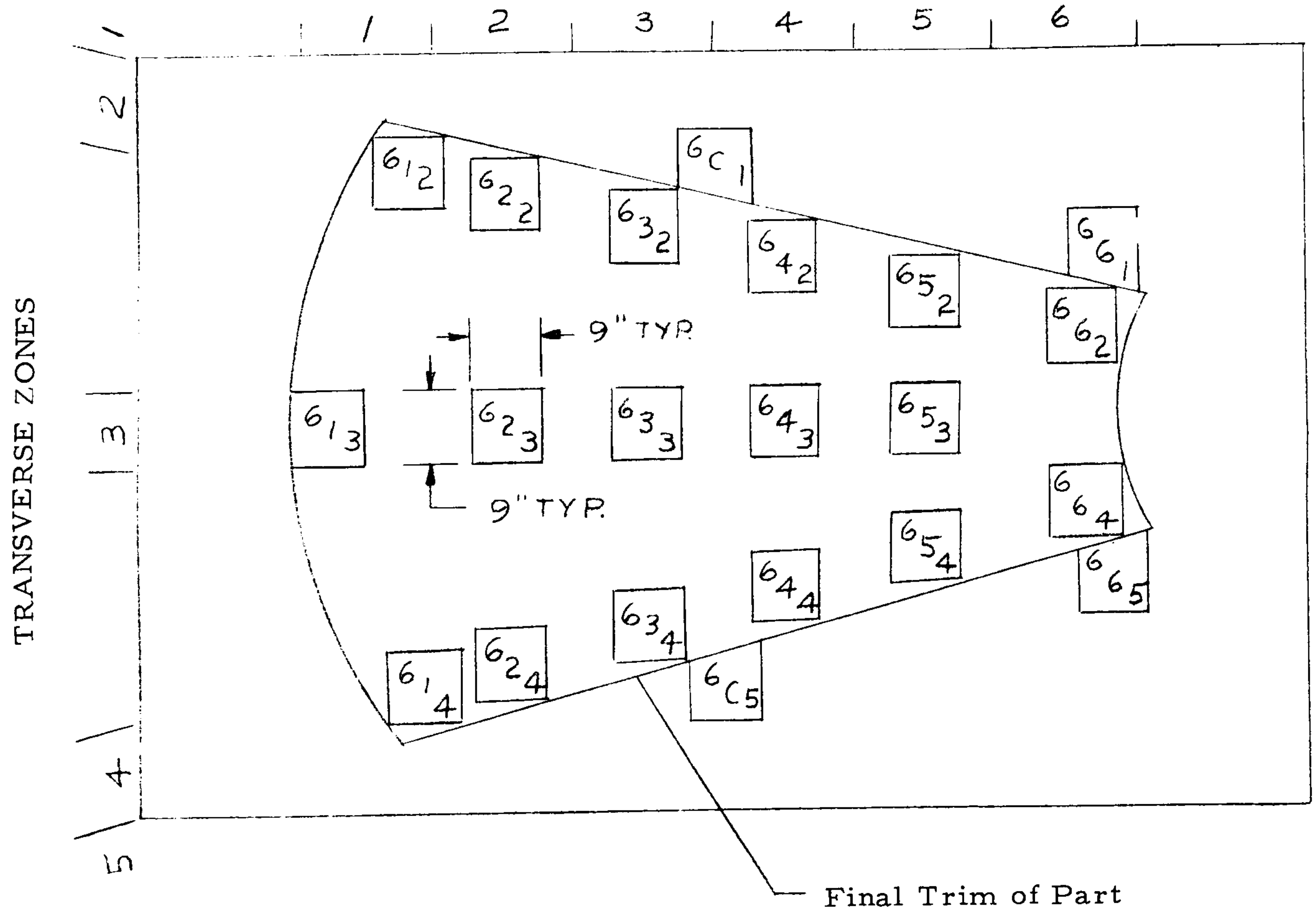
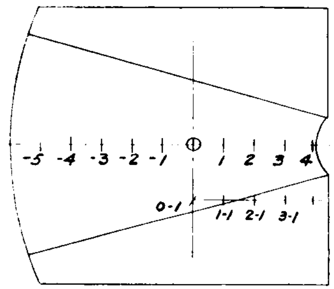


FIGURE 53. Location of Test Specimens - Qualification Part

Location	Fy x 10^3	Fu x 10^3	e%	Location	Fy x 10^3	Fu x 10^3	e%
612	52.5	61.5	13.0	6C1	51.8	61.7	12.5
	52.5	61.5	13.0		52.1	61.7	12.0
	51.7	61.6	13.0		51.7	61.9	12.5
613	52.2	61.4	12.5	661	52.0	61.4	12.5
	52.3	61.6	12.5		50.5	61.3	12.0
	52.4	61.6	11.0		51.5	61.1	11.5
623	51.5	61.3	12.5	643	52.0	61.8	13.0
	51.4	61.2	12.5		52.4	61.7	12.0
	51.5	61.4	12.5		52.3	61.7	13.0
633	50.2	60.2	13.0	653	51.7	61.1	12.5
	51.7	61.9	12.5		51.9	61.4	12.0
	53.2	63.5	12.5		52.2	61.4	12.0
6C5	52.3	60.0	12.5	624	51.4	60.7	12.5
	50.4	60.8	13.0		51.2	60.6	13.0
	51.0	61.3	13.5		51.4	60.6	12.5
614	50.9	60.9	11.5	634	50.6	60.9	14.0
	51.5	61.0	12.0		50.6	60.9	13.0
	51.8	61.2	12.5		50.3	60.6	13.5
622	52.8	62.1	12.5	644	51.7	61.3	12.0
	52.5	62.0	12.0		52.1	61.6	12.9
	52.7	61.7	12.5		52.1	61.6	12.0
632	51.8	61.9	14.0	654	52.2	61.9	12.5
	51.2	61.4	13.5		52.4	61.9	12.5
	52.0	62.0	14.0		52.2	62.0	12.5
642	51.4	61.2	12.5	664	52.8	61.9	13.0
	51.5	60.9	12.5		51.5	61.3	15.0
	51.9	61.6	13.0		50.3	60.7	13.0
652	52.0	61.6	12.5	665	43.6	58.3	14.5
	51.7	61.3	12.5		45.4	59.2	13.5
	55.4	61.4	13.0		34.9	50.2	13.5
662	49.8	58.1	12.5				
	51.5	61.4	12.0				
	52.9	62.5	13.0				

FIGURE 54. Qualification Test Results



SCHEMATIC STATION LOCATION ON 12" GRID PATTERN OF TORUS GORE SEGMENT

TORUS TANK GORE SEGMENTS

STRETCH OUT MEASURED AT IDENTICAL STATIONS OF 12" GRID PATTERN AFTER COMPLETION OF FORMING OPERATIONS

PART NO.	STATION -5	STATION -4	STATION -3	STATION -2	STATION -1	STATION 0	STATION 1	STATION 2	STATION 3	STATION 0-1	STATION 1-1	STATION 2-1	STATION 3-1
7	12 1/8	13 1/2	13 5/16	13 9/16	12 5/8	12 1/4	12 1/8	12 1/8	12 1/8	12 5/8	12 3/4	13	13 1/16
8	12 1/8	13 7/16	13 5/8	13 5/8	13	12 5/8	12 11/16	12 7/16	12 5/8	13	13 1/16	13 3/8	13 7/16
9	12 1/8	13 11/16	13 5/8	13 5/16	12 3/4	12 5/8	12 5/8	12 5/16	12 3/4	12 15/16	13 1/4	13 3/16	13 7/16
10	12 1/8	13 9/16	13 7/16	13 13/16	12 3/4	12 1/2	12 9/16	12 1/2	12 3/4	12 3/4	13 5/16	13 5/8	13 5/16
11	12 1/8	13 5/8	13 3/8	13 1/2	12 11/16	12 3/4	12 11/16	12 3/8	12 3/4	12 15/16	13 1/4	13 1/2	13 1/2
12	12 1/8	13 9/16	13 3/16	13 5/8	12 13/16	12 7/8	12 3/4	12 7/16	12 1/2	12 15/16	13 11/16	13 3/8	13 3/16
13	12 1/16	13 3/8	13 1/4	13 15/16	12 5/8	12 3/8	12 3/8	12 3/8	13	12 3/4	13 1/16	13 1/16	14 5/16
14	12 1/16	13 3/16	13 9/16	13 15/16	12 15/16	12 9/16	12 1/2	12 7/16	12 3/4	12 3/4	12 3/4	13 3/16	13 15/16
15	12 1/8	13 5/16	13 1/16	14	13 5/16	12 3/8	12 3/8	12 3/8	13 1/8	12 3/4	12 13/16	13 1/8	14
16	12 1/8	13 3/4	13 3/8	13 11/16	12 7/8	12 3/8	12 3/8	12 7/16	12 7/8	12 3/4	12 7/8	13 1/4	14
17	12 1/8	13 3/4	13 11/16	13 3/8	12 1/2	12 1/4	12 5/8	12 5/8	13	12 3/4	13	13 1/8	14 3/16
18	12 1/8	14 1/16	12 7/8	13 5/8	12 3/4	12 1/2	12 5/8	12 3/8	12 5/8	12 7/8	12 13/16	13	13 3/4
19	12 1/8	13 15/16	12 5/16	12 13/16	13 3/16	12 9/16	12 7/16	12 5/16	12 5/16	13	13 1/8	12 11/16	13 3/16
20	12 1/8	14	14	13 3/8	12 3/4	12 3/8	12 1/4	12 1/8	12 5/8	12 3/4	12 3/4	12 3/4	13 5/8
21	12 1/8	13 7/8	13 3/8	13 5/8	12 1/2	12 3/8	12 3/8	12 1/4	12 5/8	12 5/8	12 3/4	13 1/8	14
22	12 1/4	14	12 3/4	13 1/2	12 7/8	12 3/8	12 3/8	12 1/4	12 3/4	12 7/8	12 7/8	13 1/8	13 3/4
23	12 1/8	13 3/4	13 3/4	13 7/8	12 5/8	12 3/8	12 5/8	12 1/2	13	12 5/8	13	13 3/8	14 1/4
24	12 1/8	13 3/4	13 1/4	13 3/8	12 7/8	12 3/8	12 3/8	12 3/8	12 7/8	12 3/4	12 3/4	13 1/4	13 7/8
25	12 1/8	13 3/8	13 1/4	13 3/4	13 1/2	12 3/8	12 3/8	12 1/4	12 5/8	12 3/4	12 7/8	13 1/16	13 1/2
26	12 3/16	13 13/16	13 1/4	13 11/16	13 1/16	12 9/16	12 7/16	12 7/16	12 11/16	12 15/16	12 13/16	13 3/16	13 5/8
27	12 3/16	13 15/16	12 15/16	12 13/16	13	13 5/8	12 3/4	12 1/2	12 7/8	13 1/16	13 3/16	13 3/4	13 9/16
28	12 1/8	13 13/16	13 3/16	13 3/16	13 1/8	12 1/4	12 3/8	12 13/16	12 13/16	12 9/16	12 9/16	13 3/8	14 1/4
29	12 3/16	13 15/16	13 1/8	14 1/8	12 1/8	12 1/4	12 7/16	12 3/8	13 9/16	12 1/4	13	13 5/8	14 5/16
30	12 1/8	13 9/16	13 1/8	14	12 1/8	12 7/16	12 15/16	12 1/2	13	12 7/16	13 7/8	13 1/8	14
31	12 3/16	13 13/16	13 1/4	14	12 1/16	12 9/16	12 15/16	12 1/4	12 13/16	12 3/8	14 1/8	13 1/4	13 7/16
32	12 1/8	12 13/16	12 11/16	13 3/16	13 11/16	13 3/16	13 3/16	12 9/16	12 7/8	13 1/2	13 1/2	13 1/8	13 3/4
33	12 1/8	13 5/8	13 1/16	12 15/16	12 5/8	12 7/8	13 1/16	12 5/8	13 1/16	12 15/16	13 7/8	13 5/16	13 7/8
34	12 1/8	13 1/2	12 7/16	12 13/16	13 3/16	13 9/16	12 11/16	12 3/4	13 5/16	13 5/16	13 5/8	13 1/16	14 5/16
35	12 1/8	13 13/16	13	13 3/4	12 7/8	13 1/16	13 3/8	12 1/2	13 1/16	13 3/16	13 7/8	13	13 15/16
36	12 1/8	13 7/16	12 5/8	13 7/16	13 1/4	12 15/16	12 9/16	12 1/4	13	13	13 1/4	12 3/4	13 9/16
37	12 1/8	13 9/16	12 3/4	13 1/16	13 3/16	13 1/8	12 13/16	12 5/16	12 5/8	13 7/16	13 5/8	13 1/8	13 1/8
SP	12 1/8	12 13/16	12 3/4	13 5/16	13 5/16	13 1/4	12 7/8	12 7/16	12 9/16	13 7/16	13 7/16	13 3/16	13 5/16

FIGURE 55. Final Stretch Pattern for Production Parts

Upon completion of the forming tests, a series of heat treatment test operations were conducted on the die using Parts 2 and 3. These tests included the complete operation of solution heat treat, spray quench, and artificial age. During these operations, the part temperature tolerance and the quench rate were checked to insure that they were in conformity with the criteria established by the metallurgical testing and evaluation program to meet the specified requirements. In addition, different methods of attaching thermocouples to the part were tried and evaluated. It was determined that the best method of establishing the quench rate consisted of encasing the thermocouple in the center of a flattened aluminum tube having a wall thickness half that of the .125" sheet, then welding the tube to the torus segment.

Parts 4 and 5 were then solution heat treated and aged on the die in preparation for delivery to NASA. Heat treatment was in accordance with the proprietary Alcoa T63 method for which Republic is a licensee.

Upon completion of the solution heat treat and artificial age cycles, the parts (4 and 5) were located on the combination trim and check fixture. The part was strapped down, trim lines scribed and the part trimmed to size bv reciprocating saber saw and deburred with a disc sander (Figure 56). Test specimens were cut from the sheet in areas outside the trim of the part (Figure 57) and sent to the quality control laboratory for testing for tensile yield and ultimate strength and for percent elongation.

Dimensional checks were made to determine contour deviations from the fixture and to assess distortion of the part during the spray quench operation.

Upon completion of trimming and inspection operations, the part was cleaned in a trichlorethylene vapor degreaser. This was followed by a quick dip in a nitric acid and sodium sulphate solution and rinsed in cold water. The segments were then identified, trim lines marked, and packaged in a clear plastic film to protect the surface during shipping.

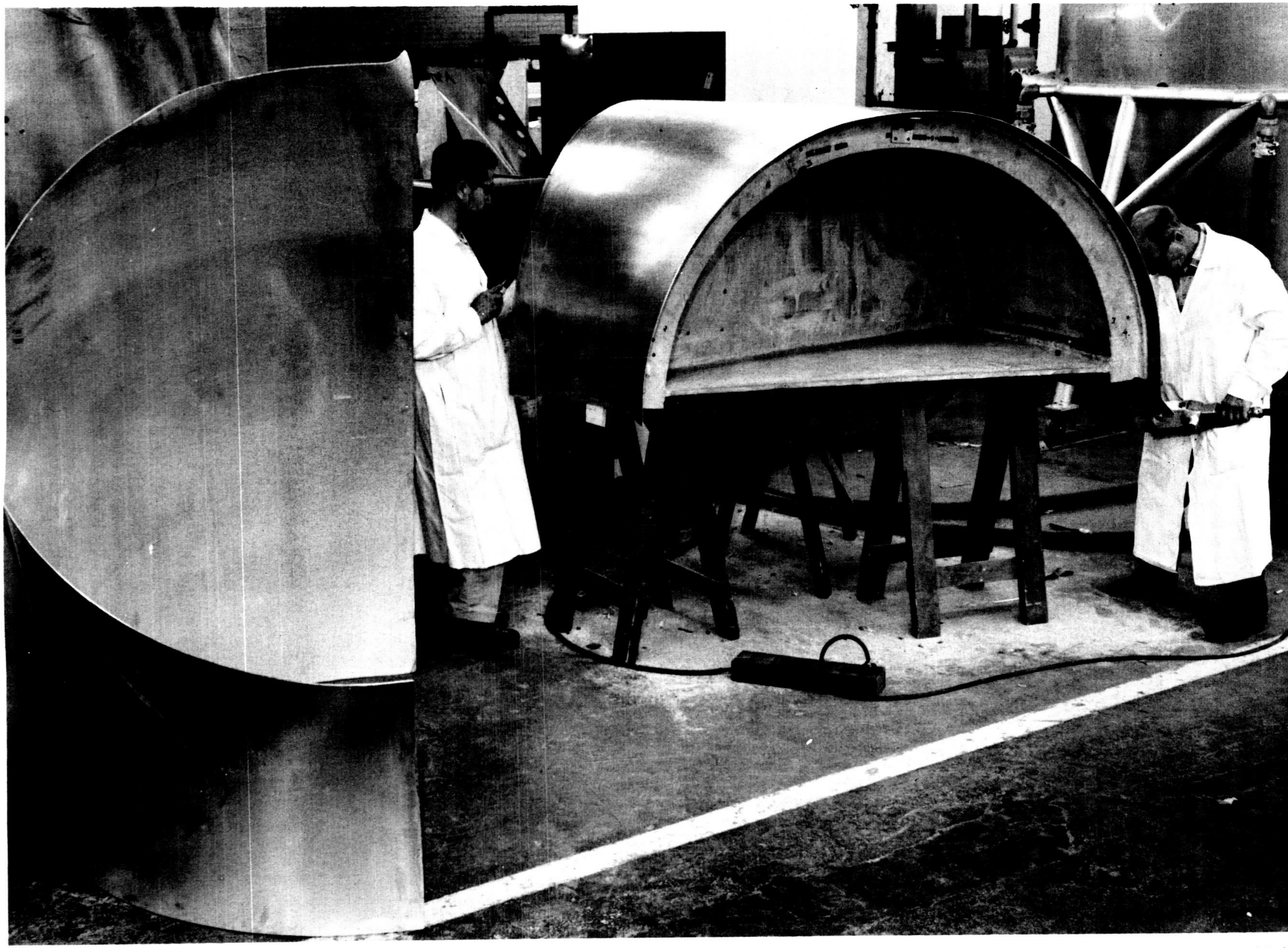


FIGURE 56. Trimming Operation with Part Located on Trim and Check Fixture MR4042

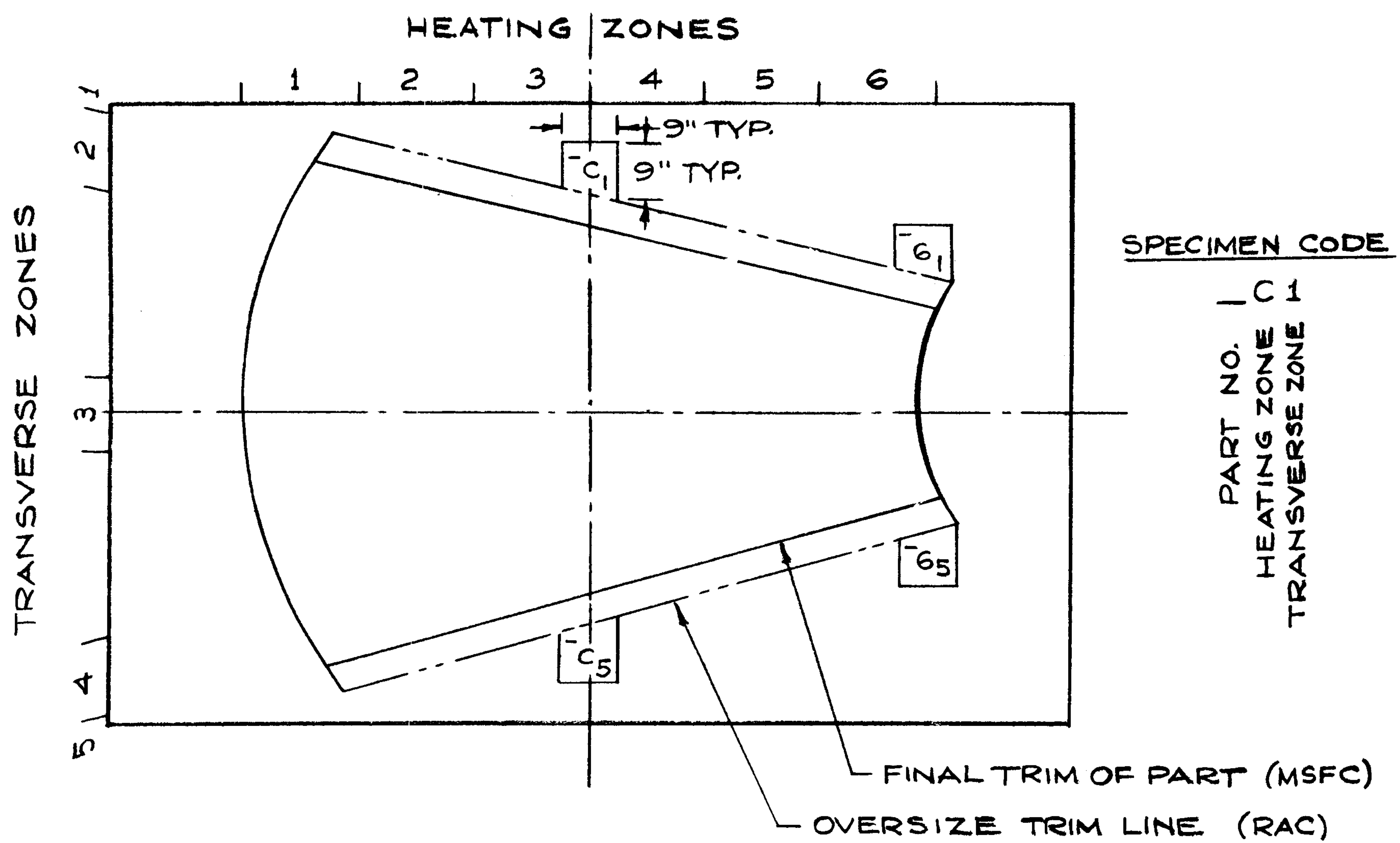


FIGURE 57. Location of Test Specimens

D. TITANIUM FORMING TEST

Upon completion of the forming and heat treating of the 7039 aluminum alloy parts, it was intended to perform forming and heat treat tests using 0.125-inch x 48 x 144-6Al-4V titanium sheet. Due to a schedule conflict, it was decided to postpone the test until completion of contract NAS 8-12911, "Hot Drape Forming of X7106 Aluminum Alloy Semi-Toroidal Bulkhead Segments per SK30-1-860." This contract is a follow-on to the contract covered in this report and utilizes certain tool components used in this program. This accounts for the slightly different contour as shown in the photographs in this section.

The die, designed for forming aluminum alloy, did not have the power capacity to reach the solution treating temperature of the titanium alloy (1725°F). As a result, it was necessary to have the material solution treated off the die, drape formed in this condition followed by aging on the die. This solution treating resulted in a loss in overall length of the sheet due to trimming of the material held in the straightening jaws. It was found necessary to lengthen the sheet by spotwelding strips on one end in order to obtain the required grip length.

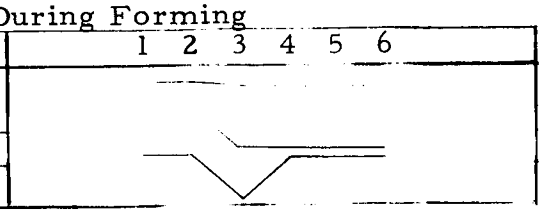
1. PART FORMING

Preparation of the titanium sheet followed the pattern established with the aluminum alloy. A grid was drawn to enable the operator to visually determine gauge thinout. Thermocouples were affixed to record and control part zone temperature.

Forming was initiated in the convex area by actuation of that jaw followed by forming in the concave area. Temperatures were varied to selectively control the ductility of the part as shown below. During forming, insulating blankets were used to achieve the desired temperature.

Changes in Heat Pattern During Forming

ZONE	1	2	3	4	5	6
Initial Temp.	550	550	500	500	500	500
Change 1	900	900	500	500	500	500
Change 2	900	900	500	900	900	900



In Figure 57 is shown the part during the forming operation.

Following the forming operation, the part was covered with an insulating blanket and aged at 1000°F for four hours (Figure 58).

2. RESULTS

The part was marked off in a modified 12-inch grid pattern. Changes in this pattern due to forming are shown in Figure 59 with a maximum change to 12-9/16-inch or an elongation of 4.7%. Material gauge thickness of the completed part was determined by vidigage and is shown in Figure 59.

Contour deviations were measured to a checking fixture and depicted in Figure 60. Coupons were cut from the formed part and tensile specimens prepared and tested. Results indicated a minimum yield strength, ultimate strength, and percent elongation of 145,970 psi, 157,855 psi, and 12% and an average of 150,000 psi, 164,000 psi and 12.5%, respectively.

3. DISCUSSION

The drape form tool and power supply were designed to form and heat treat aluminum and were not equal to the task demanded of them in the case of titanium. Difficulty was experienced in reaching desired forming temperatures even though insulation was employed to minimize radiation losses. Uniformity of temperature throughout the part during the aging cycle was not considered completely satisfactory.

It was not possible to completely form the part to the die configuration as indicated in Figure 60 due primarily to the limited capacity of the tool. That the capacity was exceeded can be seen in Figure 61. The forces exerted actually bowed the frame and wrinkled the paint.

Mechanical properties achieved as a result of the forming and heat treatment exceeded the minimum mechanical property requirements of the 6Al-4V sheet material.

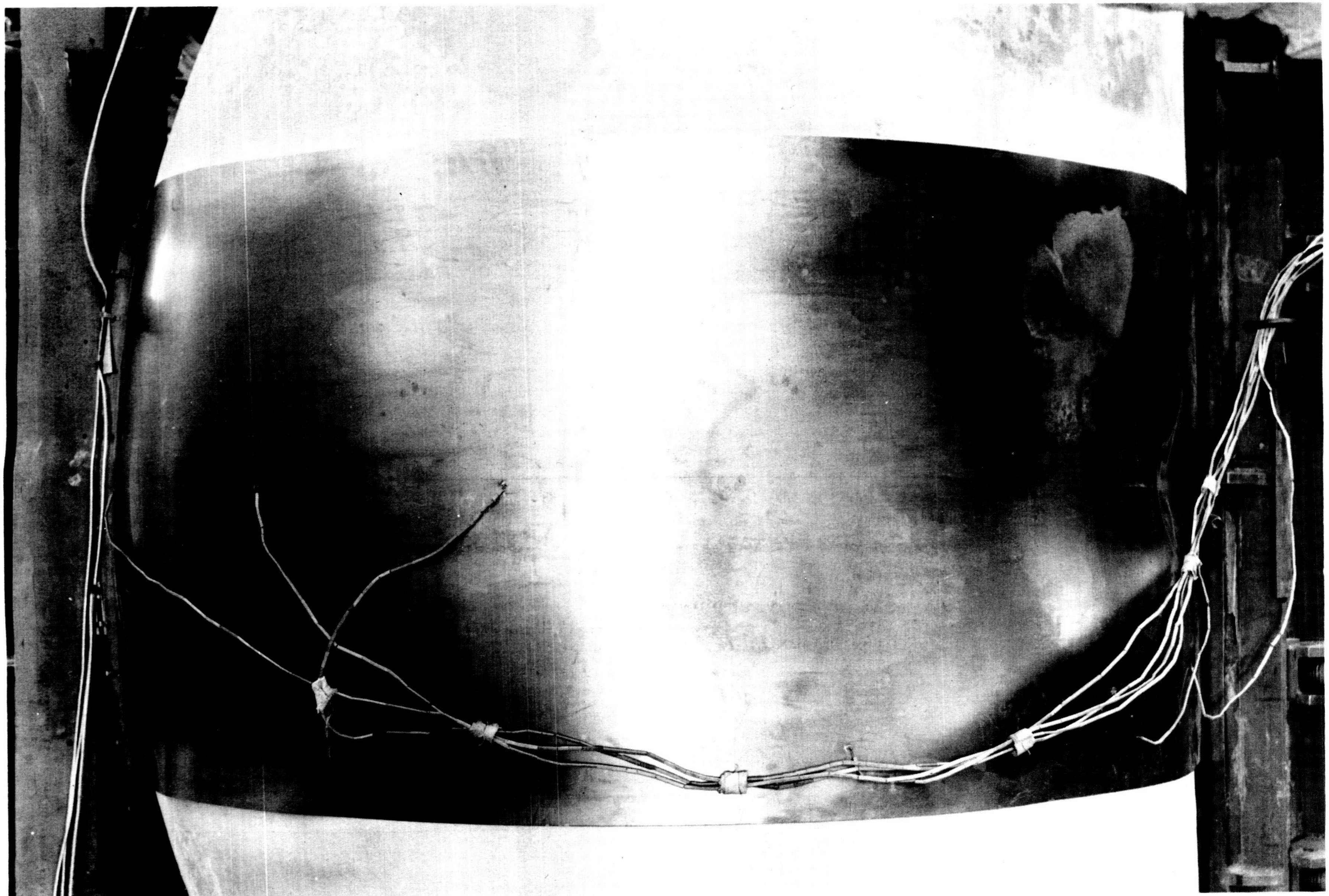


FIGURE 57. Titanium Gore Segment being Incrementally Hot Formed with Thermocouples Attached to Provide Actual Specimen Temperature

MR4526

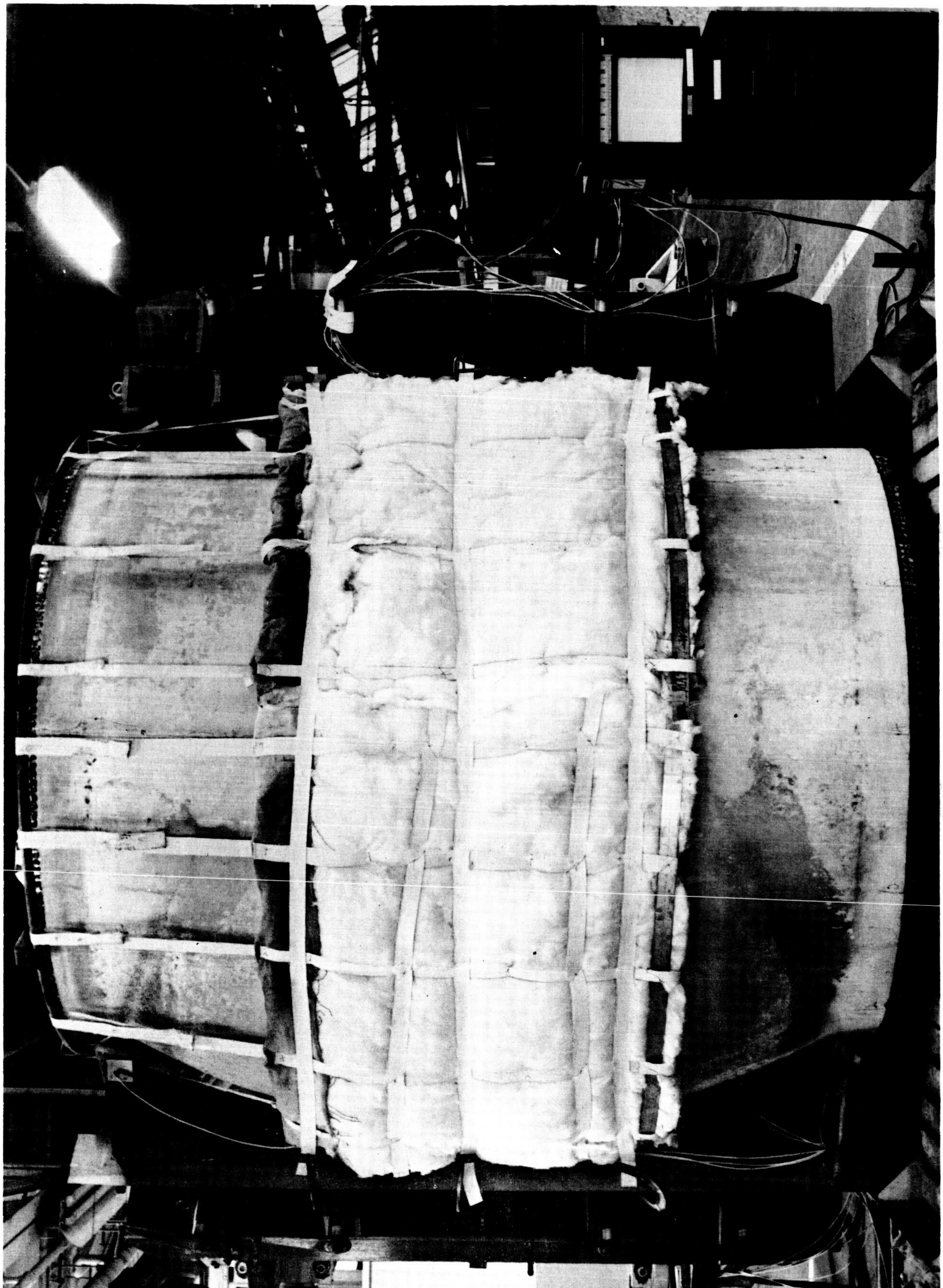


FIGURE 58. Aging of 6Al-4V Titanium Part at 1000°F

MR 4529

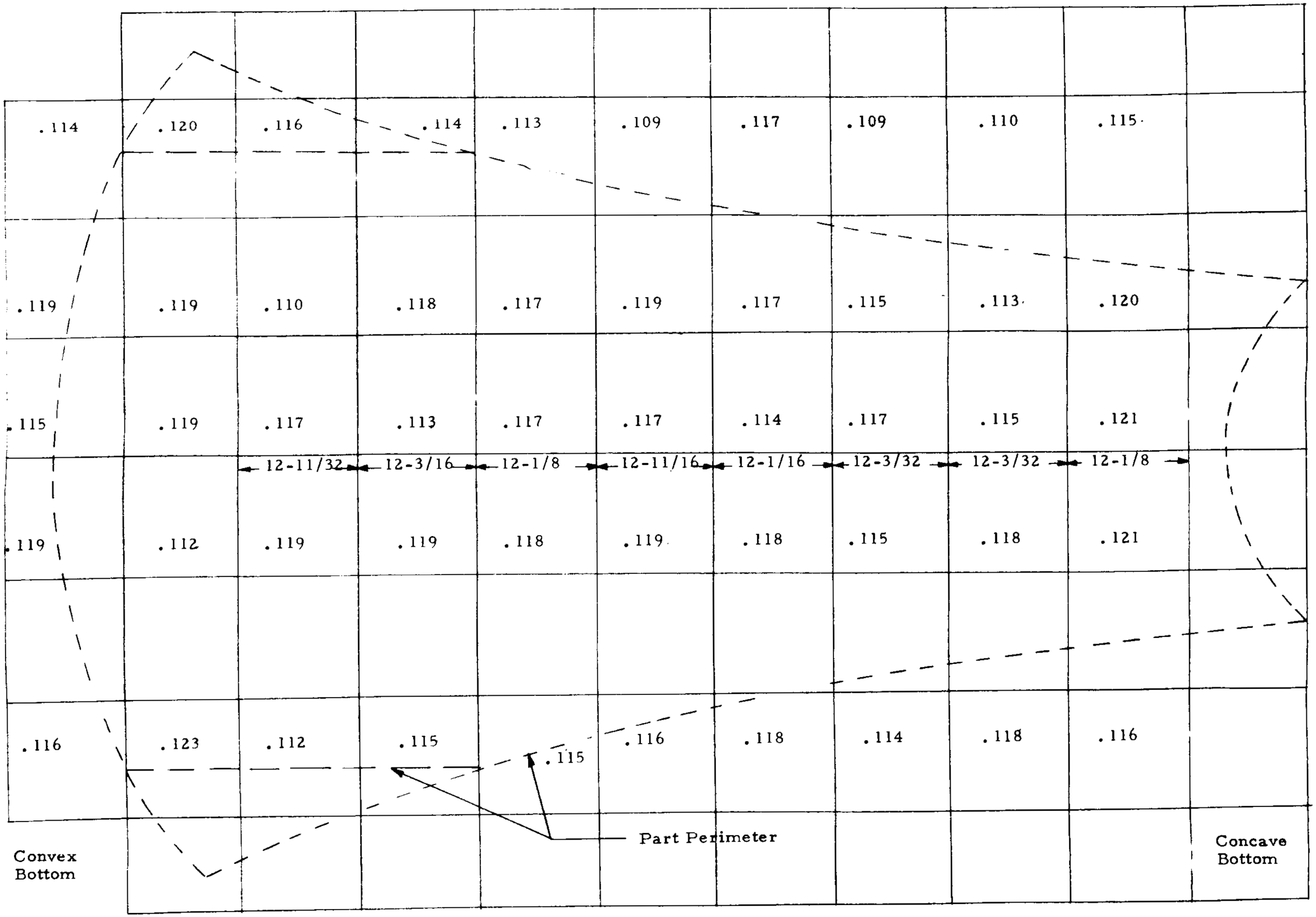
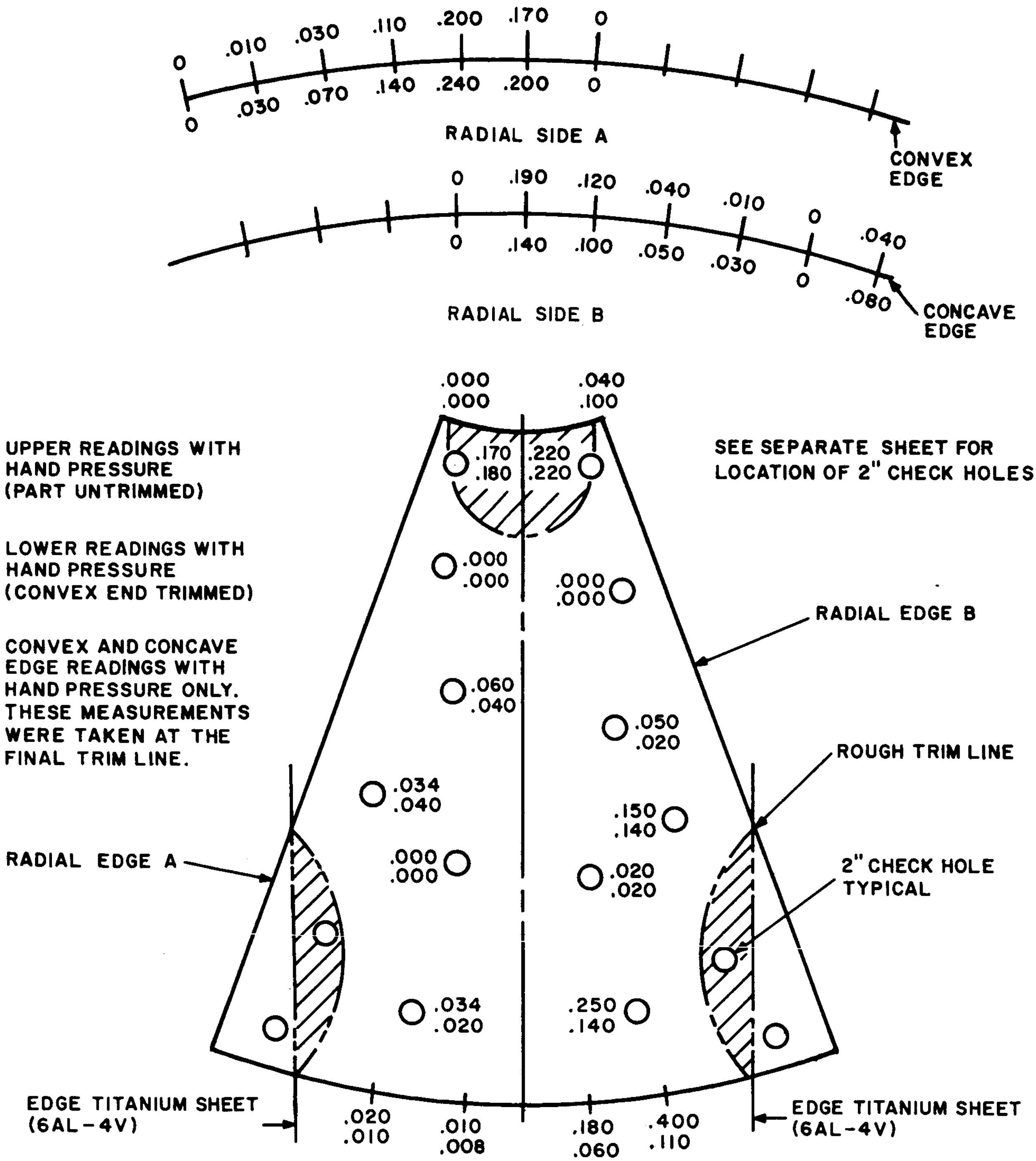


FIGURE 59. Stretch Pattern Material Thickness



Titanium Part Contour Deviations

FIGURE 60

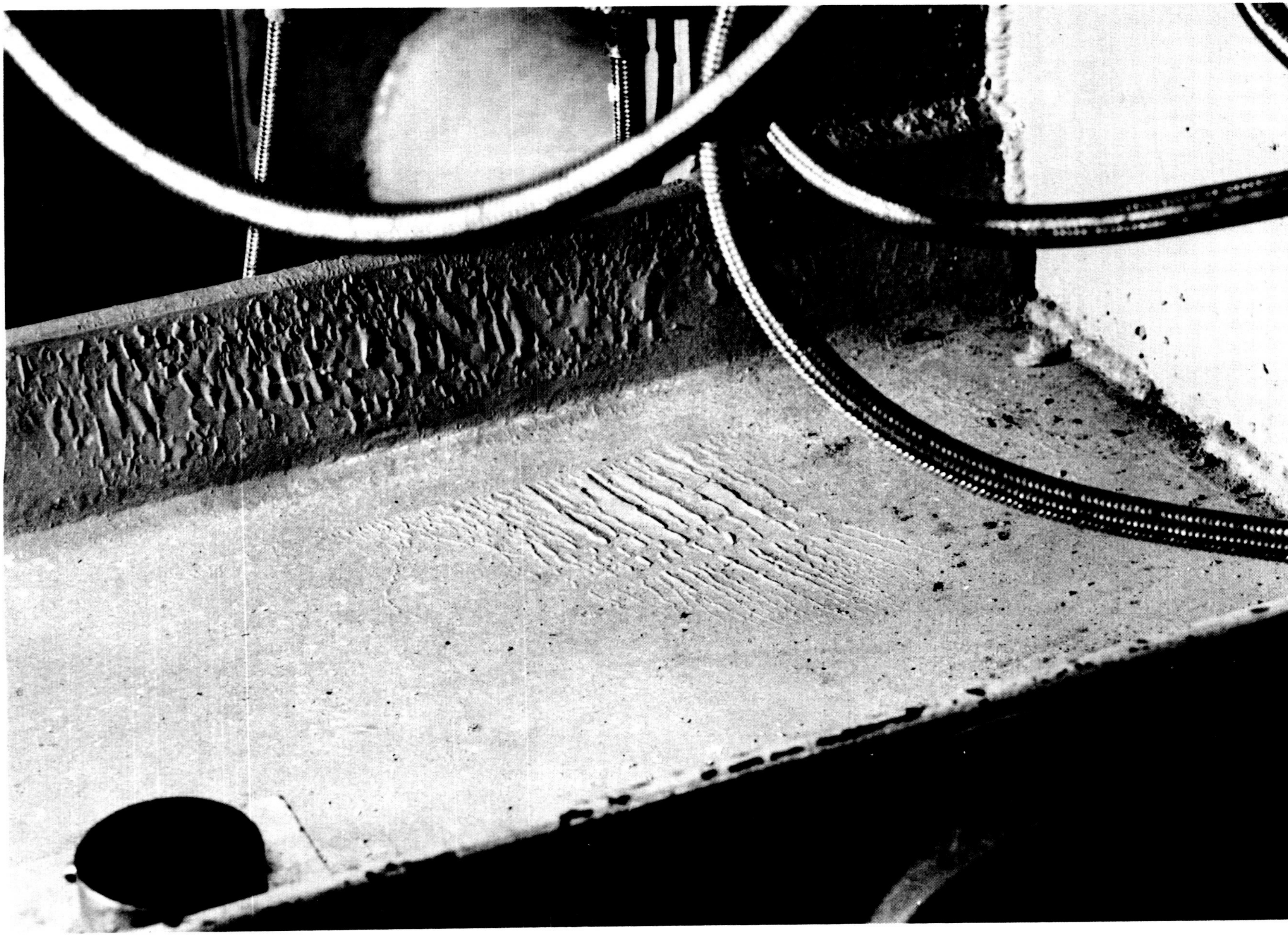


FIGURE 61. Point Wrinkling Due to Excessive Forces Developed During the Stretch Wrapping of the .125 Titanium Gore Segment

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4. CONCLUSIONS

As a result of the limited work performed, it is clear that the hot drape forming method is applicable to the forming and heat treatment of titanium alloys. Despite a structural rigidity, a power supply and temperature control that were marginal in relation to the requirements, a 6Al-4V titanium alloy sheet was formed and aged on the die.

A tooling package with a capacity significantly larger than the demands upon it and the employment of a more sophisticated method of insulating the die and part are obvious requirements for any future programs in this field.

E. HOT DRAPE FORMING

DISCUSSION

Throughout the program, a number of problems arose that resulted in the modification of the tooling package and the perfection of fabrication techniques. The forming operation showed that the control of zone temperatures, based on the monitoring of the 12-inch grid pattern, permitted the forming of parts with excellent dimensional control and minimum material thinout. Some difficulty was encountered in forming parts without wrinkles. This was due to the limited amount of stretching capability built into the tool. In order to accommodate the minimum length of material furnished by NASA, the wiper plates were designed to home on the die. A design for a longer sheet of material would have permitted the design of a mechanism to allow the wiper plates to swing past the base of the die. This would have resulted in a greater degree of flexibility in the forming process.

Each of the six zones contained two circuits of heating elements connected in parallel in the die and the two of them connected in series to the weltronic controller (Figure 62).

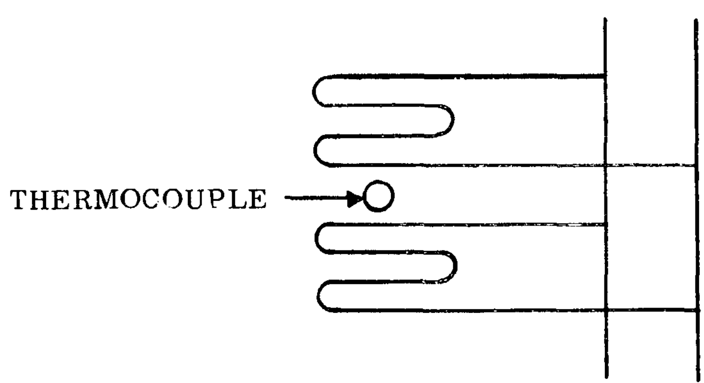


FIGURE 62

The control thermocouples were imbedded in the die in the middle of the zone between the two circuits. A failure in one of these parallel circuits, therefore, was not readily detectable. The only indication of a failure being the extended heatup time necessary to reach the desired temperature. The addition of a monitoring system consisting of a current and voltage type hook up to the controllers or a high-low limit light transformer scanner would serve to instantly detect a failure in the heater element circuitry.

During the solution heat treat cycle, the temperature control of the part was held to 840 $\pm$ 40°F. This was adequate for the solution heat treatment but a closer control of temperature was felt to be both desirable and possible. A number of factors contributed to this temperature variation:

1) Large radiation losses over a constantly varying contoured surface

2) Variation in depth of the heating elements from the die surface

3) Electrical pickup induced into the thermocouple circuits

4) Localized areas where the part was not in contact with the die because of the limited stroke of the jaws.

The introduction of the insulated doors which could be pivoted in place over the part contributed measurably to the decrease in radiation losses and to the stabilization of temperature. Nevertheless, there was a time lag and a resultant uneven temperature drop when the insulated doors were swung out of position, the spray hood rolled into place and the quench water turned on. The problem of the uneven temperature drop, coupled with the difficulty in locating the doors in exactly the same position for each part, led to the conclusion that a better method would be to combine the insulated doors and the spray hood into a single unit. An insulated spray hood equipped with circulating fans more closely simulates a furnace condition during heat treat and would have the advantage of permitting immediate spray quenching of the part when desired.

The nichrome heating elements were set a uniform distance below the die surface to ensure that the temperature at the interface between die and part was uniform throughout. The standard method employed in this operation was both tedious and time consuming and it was difficult to maintain a uniform depth in all areas due to contour variation.

The controller thermocouples imbedded in the die were unshielded and subject to electrical pickup from the 440-volt heating element circuit. This caused spurious signals to be sent to the controller and constant temperature was difficult to maintain. The use of shielded and ungrounded thermocouples eliminated this problem.

In some instances there were local areas not in contact with the die when the part was remounted on the die for the artificial aging cycle, and this resulted in thermal variations over the part. This condition was due, primarily, to the inability to apply tension to the part because the actuating cylinders had passed through their full stroke, and the wiper plates had homed on the die. This was compensated for by taking great care in forming to ensure that there would still be some stroke remaining after completion of the solution heat treat. A die designed to permit the wiper plates to swing past the base of the die easily remedies this situation.

During the program, two of the heating element wires failed and caused a temperature drop in one of the zones. It was not immediately detected because of the parallel circuitry employed. However, when the defective wires were discovered, they were immediately replaced and forming continued. The number of parts heat treated with a cool zone was not established because the test coupons used to determine mechanical properties of the skin were taken outside of the trim of the part in a zone other than the one in which the failure occurred. Since only non-destructive testing could be applied to determine strength levels inside the part it was decided to introduce a hardness testing procedure after establishing a reasonably close relationship between material hardness and strength.

Specimens previously used for mechanical properties testing were utilized to establish suitable hardness comparator readings. A Webster comparator was used to check the hardness along the edges of the part, and a Barber-Colman (Barcol) comparator was used to check the areas within the part. These readings indicated low properties in areas of skin numbers 24 through 29. However, the readings were not consistent enough to clearly indicate that the low values were entirely due to the element failure in the die. A close examination of the next part during the aging cycle disclosed that there were gaps between the part and the die in the area along the top and bottom trim of the part in zone 3. This is the same area in which difficulties were encountered in moving the forming bubbles out past the trim of the part during earlier forming tests.

The fact that the actuating cylinders had no additional stroke remaining precluded the tightening of the part against the die during the aging cycle. A design change to permit a longer stroke (having the wiper plates move past the base of the die) and utilizing a longer blank, would eliminate this problem.

Thermal Processing Difficulties

During the program, it was found that mechanical property specimens taken from several of the torus tank segments did not meet the target properties set for 7039 T63. Investigation revealed that several of these segments had been processed while the ceramic die contained a broken heating element. In addition, it was learned that an air gap existed between a portion of some of the skins and the die during processing. Either of these deficiencies could have resulted in improper thermal treatment in these areas and in subsequent reduction of mechanical property values due to insufficient solution treatment, artificial aging, or both.

A third possibility for reduced results was that of overaging, due to accidental contact of the part with the hot ceramic die after solution treatment and quenching had been effected. Tests performed at Republic have shown that 7039 is quite sensitive to this difficulty and that relatively short contact times would be sufficient to considerably reduce the properties obtained.

Laboratory Tests

In order to determine the cause of the difficulty and its extent without destroying the parts, it was first necessary to devise a means of nondestructive examination of the segments. This problem was complicated by the size and the geometry of the parts involved and the lack of support that is required for conventional hardness testing equipment. After experimentation with other devices (eddy current, surface conductivity devices), the Barcol portable hardness comparator was selected for this purpose.

The instrument was found to be a useful tool for predicting the approximate mechanical properties achieved by this alloy. A minimum of support was required for a Barcol survey and the indentation produced as a result of this technique was considered negligible. Because this instrument requires a plane surface for accurate readings, a special shoe was devised to compensate for the curvature of the part. The technique was used with 7039 after previously tested mechanical property specimens were used to establish a suitable calibration relationship between the hardness of the material and its strength. Although the instrument is sensitive to operator technique, it was nevertheless found to be satisfactory for screening purposes and it was used to estimate the variation in properties of this alloy (typical values of hardness versus strength are given in Figures 63 and 64).

Barcol readings accomplished the following:

1) Determined what fraction of the total number of parts was affected.

2) Determined the degree of departure from target properties in various areas of each part.

3) Classified parts into categories based on satisfactory, intermediate, and unsatisfactory hardness values for future property improvement.

4) Determined whether a suitable salvage process could be devised for low strength parts.

Concurrent with this study, laboratory tests were performed on specimens taken from the nozzle sections and from the remaining trim of low property torus segments.

Artificial aging in a furnace was performed on tensile specimens from nozzle sections which had been removed from the part subsequent to solution treatment (but prior to aging on the die). These tests resulted in satisfactory aged properties, and the conclusion that neither the broken elements nor the air gaps had affected the solution treatment of the part.*

---

* Apparently the thermal insulation blanket used during solution treatment allowed the material in all zones to reach a temperature high enough in the solutioning range to permit proper treatment regardless of the broken elements or the presence of air gaps. Since the temperature tolerance during aging is more critical, it was felt that at least some of the parts had been underaged.

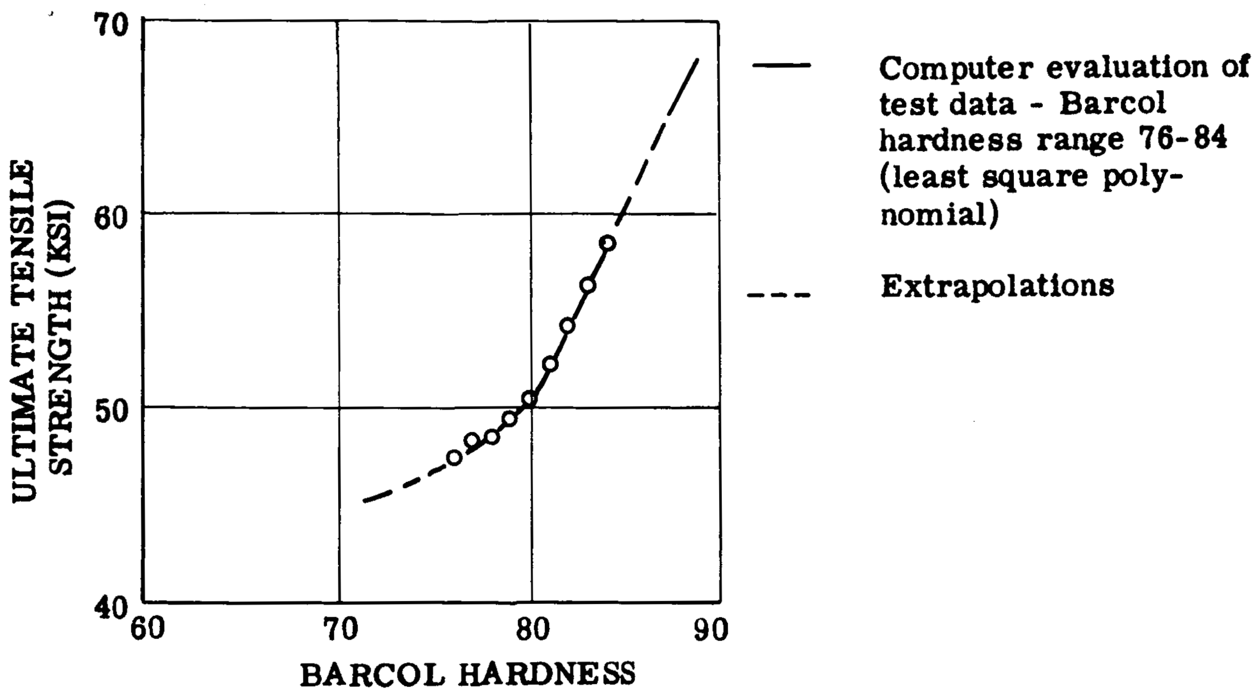


FIGURE 63. Correlation of Barcol Hardness with Tensile Strength - 7039

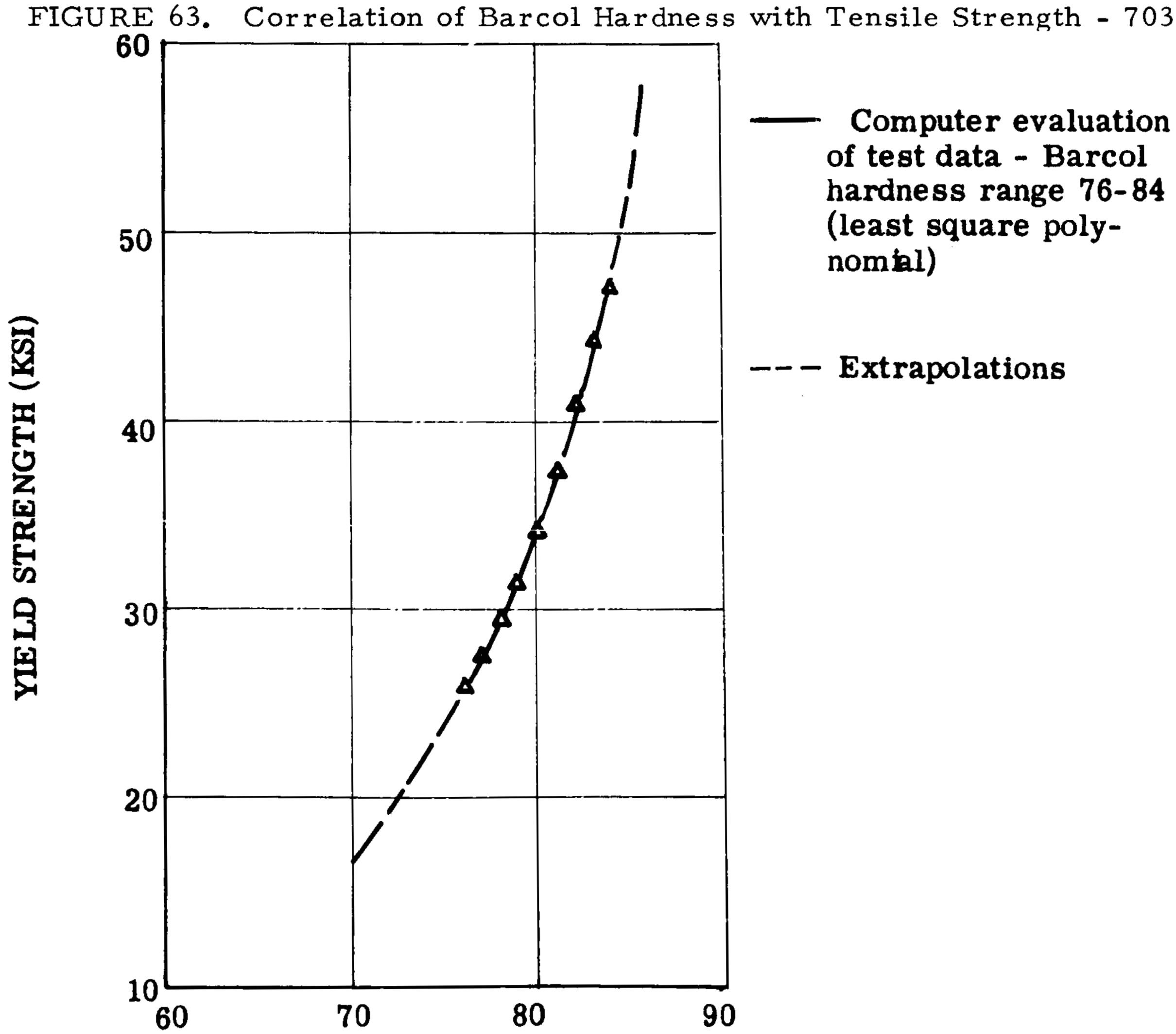
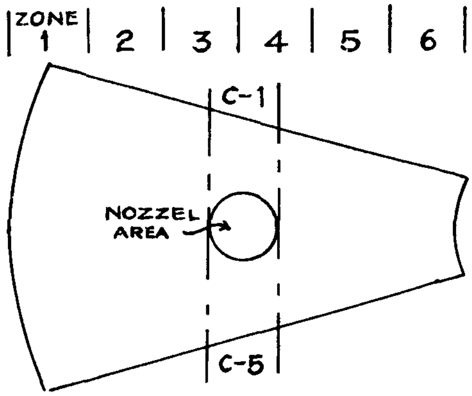


FIGURE 64. Correlation of Barcol Hardness with Yield Strength - 7039



Area	Fty	Ftu	% E
C-1(aged on die)*	36.3	55.1	18.1
C-5 (aged on die)*	43.9	58.7	17.6
Nozzle (aged in furnace)*	50.7	60.5	12.0

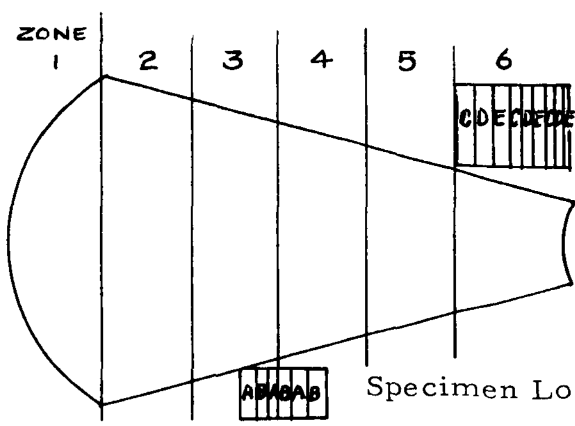
*Values given are the average of three tests

These tests also indicated that quenching had been performed satisfactorily and that it had been rapid enough to produce satisfactory properties in properly (furnace) aged parts.

To determine whether the low value areas of torus tank segments would respond to additional aging, tensile coupons were taken from low property zones of the parts. This was determined by a Barcol hardness survey and confirmed as follows:

Every second specimen was tested in the as-received condition (solution treated and aged on ceramic die) and the remaining were given an additional treatment of 300° F for three hours and then tested.

In addition, specimens were taken from areas in the same tank where Barcol predictions (and mechanical property tests) indicated acceptable mechanical properties. Every third specimen was tested in the as-received (ceramic die processed) condition; the ones adjacent were heat treated for three hours at 300° F and tested, and the third set was heat treated for six hours at 300° F and tested.



Specimen Location

The purpose of this series of tests was as follows:

1) To demonstrate that an additional 300°F for three hours would allow underaged areas to respond favorably and achieve the proposed target properties of 48,000 psi yield strength and 57,000 psi ultimate strength.

2) To demonstrate that areas already at this strength level would not be adversely affected by as much as six additional hours at the aging temperature.

The data presented in Table 5 below show that both these premises were substantially correct. (The effect of the supplemental treatment on the subsequent corrosion resistance was not tested; however, both Alcoa and Republic feel that no detraction in corrosion behavior would result from this process.)

TABLE 5. THE EFFECT OF SUPPLEMENTAL HEAT TREATMENT ON THE 7039 ALUMINUM ALLOY

Specimen Area	Condition	Fty (ksi)	Ftu (ksi)	%E (2")	Barcol Hardness	
					As Rec'd	After Supplemental Heat Treatment
26C-5-A	As rec'd** (low property areas)	33.4	54.6	19.2	77	
26C-5-B	As rec'd + 3 hours at 350°F	48.9	59.7	12.2	77	81
26-61-C	As rec'd** (satisfactory property areas)	49.7	59.1	11.2	82	
26-61-D	As rec'd +3 hours at 350°F	49.0	59.3	11.2	81	81
26-61-E	As rec'd + 6 hours at 350°F	48.6	59.2	10.5	80	81

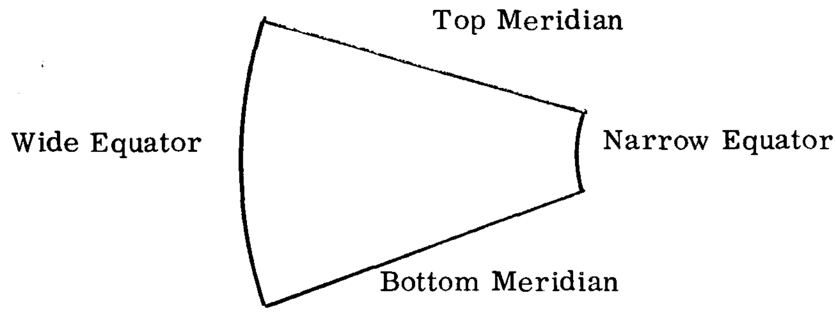
* Mechanical properties are the average of three tests for each condition

** Refers to the condition of the torus tank after solution treatment and aging on the ceramic die

Additional data showing the effect of aging technique and of time and temperature on the mechanical properties of 7039 is shown in Table 6 and Figure 65. As a result, the conditions for the supplemental treatment were modified to include an eight-hour exposure at 300° F.

Tests on Full-Size Parts

Barcol hardness readings were taken at 4-inch intervals at the final trim perimeter and at selected internal areas of 21 torus tank segments. All of these parts exhibited a similar pattern, i. e., low hardness values were recorded coincident with the narrow equator.



The cause for this is attributed to the proximity of this zone to the steel jaws on the ceramic die with the attendant loss of heat to the jaws. As a consequence, this area was not completely solution treated and therefore could not respond fully to the aging process. Future work with hot drape forming, therefore, should incorporate a part with enough material in this zone to permit the trim line to be sufficiently removed from the jaw areas.

At a distance of one inch within trim, most of these values were significantly higher and closely approached the target values. Since these segments are to be joined by fusion welding at the trim lines, it is likely that the properties in these zones would have been decreased below the expected T-63 properties in any event.

Of the 21 torus segments examined, sixteen exhibited satisfactory properties (with the exception of the area of the narrow equator, cited above) or would achieve satisfactory properties on exposure to the

TABLE 6. THE EFFECT OF TIME AND TEMPERATURE ON THE MECHANICAL PROPERTIES OF 7039 ALUMINUM ALLOY

	Yield Strength (KSI)	Ultimate Tensile Strength (KSI)	Elongation in 2"	Barcol Hardness
NA* Only	27.7	54.3	22.0	77.0
	28.4	53.9	24.0	78.0
	28.2	54.4	23.5	78.0
Average	28.1	54.2	23.2	77.7
NA + 225°F (6 hours)	26.1	47.4	21.0	77.0
	24.3	47.6	20.5	75.0
	25.9	47.3	19.5	76.0
Average	25.4	47.3	20.7	76.0
NA + 225°F (6 hours) +250°F (1 hour)	27.0	47.7	21.0	76.0
	26.0	47.4	23.0	76.0
	26.6	47.1	20.0	77.0
Average	26.7	47.4	21.3	76.3
NA + 225°F (6 hours) + 250°F (4 hours)	31.4	49.8	18.5	79.0
	30.6	49.7	18.0	80.0
	31.1	50.6	19.0	80.0
Average	31.0	50.0	18.5	79.7
NA + 225°F (6 hours) + 250°F (8 hours)	38.3	53.8	18.0	83.0
	37.0	52.7	16.0	83.0
	35.7	52.7	16.5	82.0
Average	37.0	53.1	16.8	82.7
NA +225°F (6 hours) + 250°F (16 hours)	43.0	57.2	16.5	84.0
	43.3	56.6	15.0	83.0
	43.0	56.0	14.5	83.0
Average	43.1	56.6	15.3	83.1
NA + 225°F (6 hours) + 275°F (1 hour)	31.4	48.8	21.5	
	30.6	49.1	19.5	
	30.7	48.8	19.5	
Average	30.9	48.9	20.2	
NA + 225°F (6 hours) + 275°F (4 hours)	39.8	54.7	17.5	
	39.6	54.1	15.5	
	39.4	54.6	19.0	
Average	39.6	54.5	17.3	
NA + 225°F (6 hours) + 275°F (7 hours)	43.6	56.4	16.5	
	43.4	56.7	15.0	
	46.0	57.2	13.5	
Average	44.3	56.8	15.0	
NA + 225°F (6 hours) + 275°F (16 hours)	50.7	59.9	13.0	
	50.2	59.8	12.5	
Average	50.5	59.9	12.8	

*Solution heat treated at 870°F, hot water quenched, and natural aged for five days.

TABLE 6. THE EFFECT OF TIME AND TEMPERATURE ON THE MECHANICAL PROPERTIES OF 7039 ALUMINUM ALLOY (Continued)

	Yield Strength (KSI)	Ultimate Tensile Strength (KSI)	Elongation in 2"	Barcol Hardness
NA + 225°F (6 hours)	33.4	50.4	17.0	80.0
+ 300°F (1 hour)	33.2	50.6	18.0	79.0
Average	33.6	50.6	17.2	79.3
NA + 225°F (6 hours)	45.2	57.8	11.5	83.5
+ 300°F (4 hours)	46.2	57.3	11.5	83.5
	46.4	58.1	14.0	83.5
Average	45.9	57.7	12.3	83.5
NA + 225°F (6 hours)	48.0	59.2	13.0	84.5
+ 300°F (8 hours)	47.5	58.3	12.0	84.0
	-	59.5	12.5	84.0
Average	47.8	59.0	12.5	84.1
NA + 225°F (6 hours)	46.1	60.0	13.0	84.5
+ 300°F (16 hours)	47.8	60.8	11.0	85.0
	47.6	58.9	11.5	85.0
Average	47.2	59.7	11.8	84.8
NA + 225°F (6 hours)	45.6	59.3	12.0	84.5
+ 300°F (16 hours)	45.7	59.4	12.0	84.0
300°F (3 hours)	46.5	59.4	10.5	85.5
Average	45.9	59.4	11.5	84.7
NA + 225°F (6 hours)	46.8	59.9	11.5	84.0
+ 300°F (16 hours)	47.0	60.1	13.0	84.0
300°F (6 hours)	-	59.8	12.0	85.0
Average	46.9	59.9	12.2	84.2
NA +225°F (6 hours)	48.4	58.8	11.5	84.0
+ 300°F (16 hours) +	48.9	58.9	11.0	84.0
300°F (12 hours)	48.9	59.2	11.5	84.0
Average	48.7	59.0	11.3	84.0
NA + 225°F (6 hours)	47.7	58.8	10.5	85.0
+ 300°F (16 hours) +	46.7	59.3	10.5	84.0
300°F (16 hours)	48.3	59.0	14.0	84.0
Average	47.6	59.0	11.7	84.2

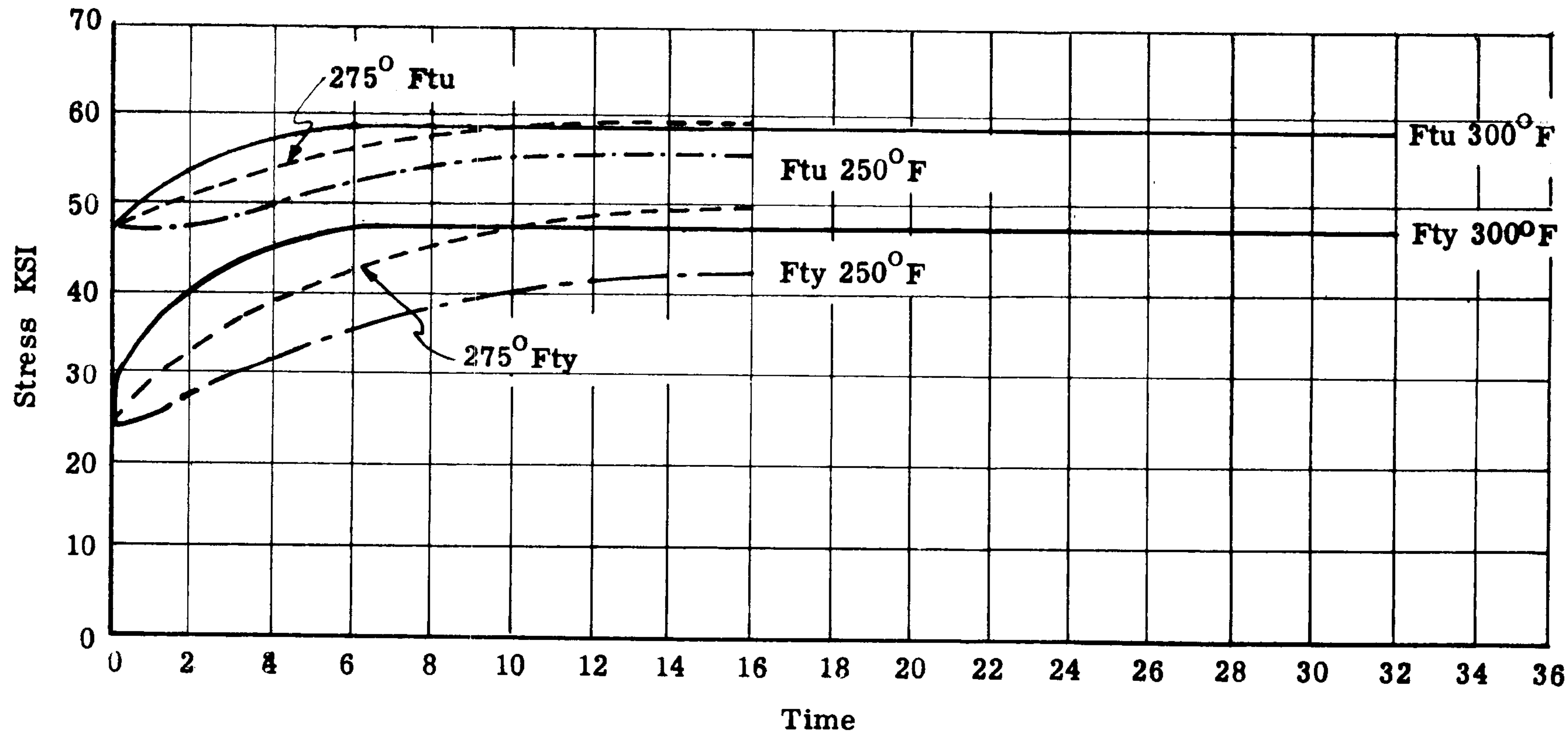


Figure 65. Aging Time (After Solution Treatment - (870)-HWQ - 5 Day Natural Age & 6 Hrs. at 225°F) Hours

supplementary heat treatment. Based on hardness values, the following segments fell into this category:

4	17/18A	12	22
5	17/18N	14	26
11	SP	20/21A	33/34A
13	Z	X	Y

Five of the segments indicated that their response to the supplemental heat treatment would be questionable. These were 33/34B, 35/31B, 29, 30, 25/31A. The cause of low properties as shown by hardness checks of these parts is attributed to accidental contact of the part with the hot ceramic during removal from the die after solution treatment.

Torus segments Numbers 12 and 29 were subjected to the supplemental of 300° F for eight hours in a furnace at NASA. The results obtained indicated a response in properties in some areas of the parts, while other areas remained at the low value. The remaining segments have not yet been exposed to the supplemental treatment.

Conclusion

In general, the hot drape forming method performed well and can be considered a significant advance in the state of the art. The forming, solution treating, spray quenching and artificial aging of thirty-three torus segments was a thorough test of this method of fabrication. It is particularly applicable to the controllable forming and complete heat treatment of large complex configured parts where its flexibility can be fully utilized.

As with all new and untried methods, there was a series of problems encountered in the specifics of forming and heat treating. These difficulties resulted in certain immediate modifications to the tooling and procedures. In addition, the following improvements are suggested for inclusion in future designs of hot drape form tooling packages:

1) A light transformer scanner system to detect failures in the circuitry and a device that will visually indicate relative current loads in each zone.

2) Combine the spray shield and the insulating doors in a single unit.

3) Use shielded thermocouples to eliminate electrical pickup from the heating elements.

4) Introduce a system of grid zone control to provide both vertical and horizontal heat zones. This would increase control of material gauge thinout.

5) Modify the die design to permit quenching from both sides of the workpiece.

SECTION II

PORT FORMING

The technique of forming flared port openings of smooth transition which offer a minimum of resistance to fluid flow and a continuous surface amenable for welding attaching conduits, was developed at the Republic Aviation Division of Fairchild Hiller Corporation under Contract NAS 8-2618, "Development of Technology for Flaring of Nozzle Openings."

Work performed under this contract indicated that port openings can readily be formed using simple tooling and pull type equipment. In essence, the method employed is to withdraw a spherical punch or ball through an undersize developed cutout while the workpiece is restrained in a matched die.

Under this program, six 3-1/4-inch diameter and eight 20-inch diameter flared ports were to be formed in fourteen of the previously hot drape formed torus segments per drawing MRD-SK-396 and 15-A-X-1110. In addition, four 3-1/4-inch diameter flared ports were to be formed in four sump sections supplied by NASA.

A. PORT GEOMETRY

Preliminary design work was done to make loft layouts of the port cutouts for the 3-1/4-inch diameter and the 20-inch diameter flared ports.

Preform cutout configurations were developed descriptively. The technique used is illustrated in Figure 66 for the case of cylindrical sections and proceeds as follows:

1) Layout the radius curvature
2) Layout a 3-1/4-inch (nozzle inside diameter) horizontal tangent to the apex of curvature (line x-y)
3) Layout additional lines parallel to the horizontal tangent in increments of 1/4-inch
4) Project the extremities of the horizontal lines to the plan view giving a 3-1/4-inch diameter circle and divide the circle radially
5) Project the intersection points of the radial lines on the circle circumference to the radius of curvature; for example, Point O, producing line A-G
6) Layout distance A-G from Point O on the radial line giving Point 6. Similarly, distance A-F yields Point 5, A-E gives Point 4, etc.

Repeating steps 5 and 6 on other radial lines results in a number of points which, when connected, represent various size preform cutouts. Six cutouts were developed for each radius of curvature tested.

The developed patterns were cut into templates and wrapped on the outside surface of the blanks to be formed for scribing the periphery of the preform cutout. The edge of the preform cutout in the blank was made normal to the blank surface at all points about the periphery.

B. TOOL DESIGN AND MANUFACTURE

Designs were drawn of the forming punches and part supports as follows:

GMT-13800 Spherical Punch 3-1/4-inch diameter port forming tool

GMT-13801 Spherical Punch 20-inch-diameter port forming tool

GMT-13802 Gore Segment Support (3-1/4-inch diameter port)
GMT-13803 Gore Segment Support (20-inch diameter port)
GMT-13804 Sump Segment Support (3-1/4-inch diameter port)

Punches - The spherical punches are machined steel tools with center holes threaded for mounting purposes. The diameters were calculated to produce 3-1/4-inch diameter or 20-inch diameter flared port openings in the workpiece, taking into account the anticipated material springback.

1. Gore Segment Support - 3-1/4-inch Diameter Port

The gore segment support is a cast kirksite female form block made to match the convex surface of the gore segment. It has a 5-inch diameter clearance hole at the location of the port (Figure 67).

2. Gore Segment Support - 20-inch Diameter Port

The 20-inch diameter gore segment support consists of a mated male and female die made of cast kirksite. It is designed to sandwich and support the gore segment during the port forming operation. It has a clearance hole and a guide hole at the location of the port (Figure 68).

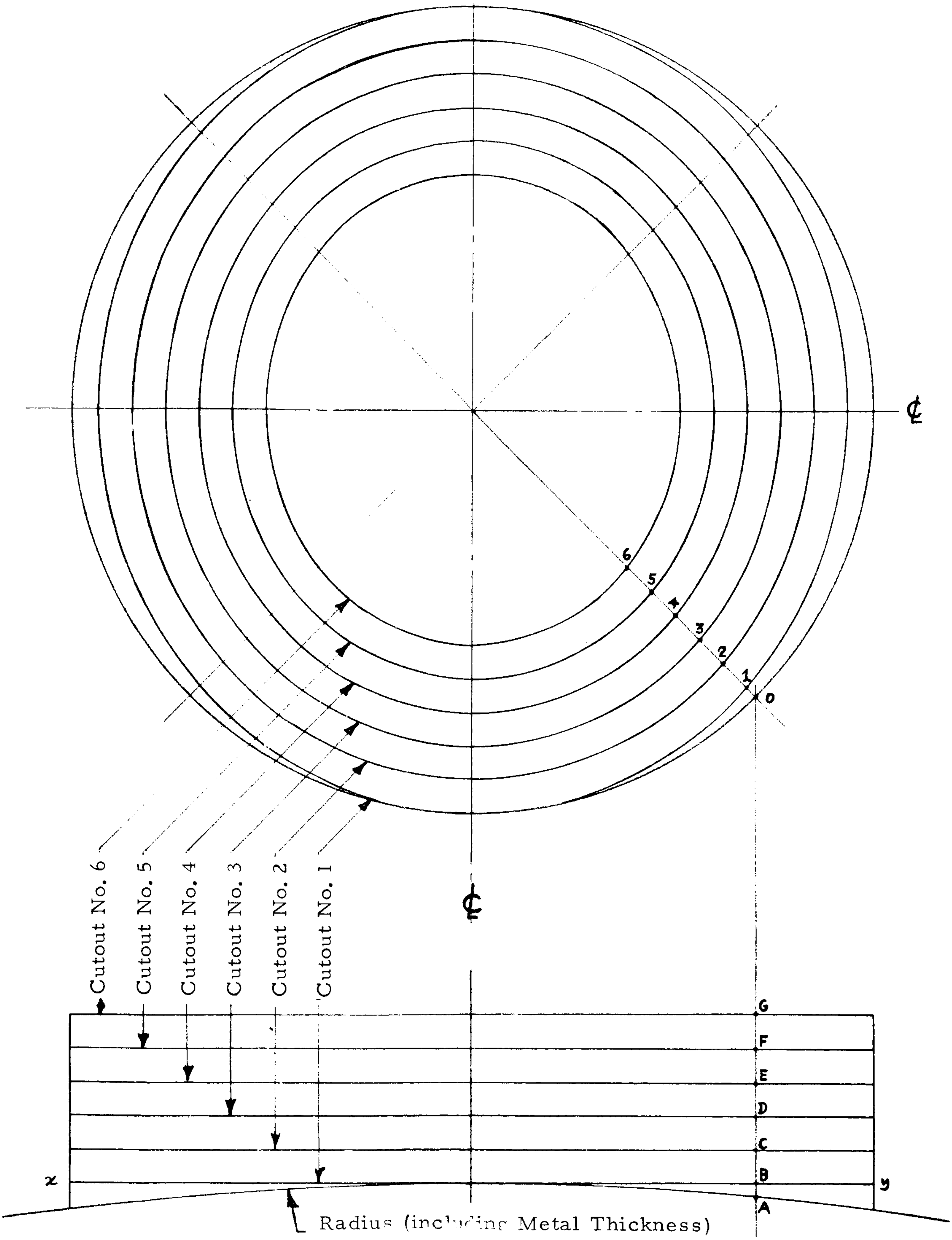


FIGURE 66. Schematic for Preform Cutout Development

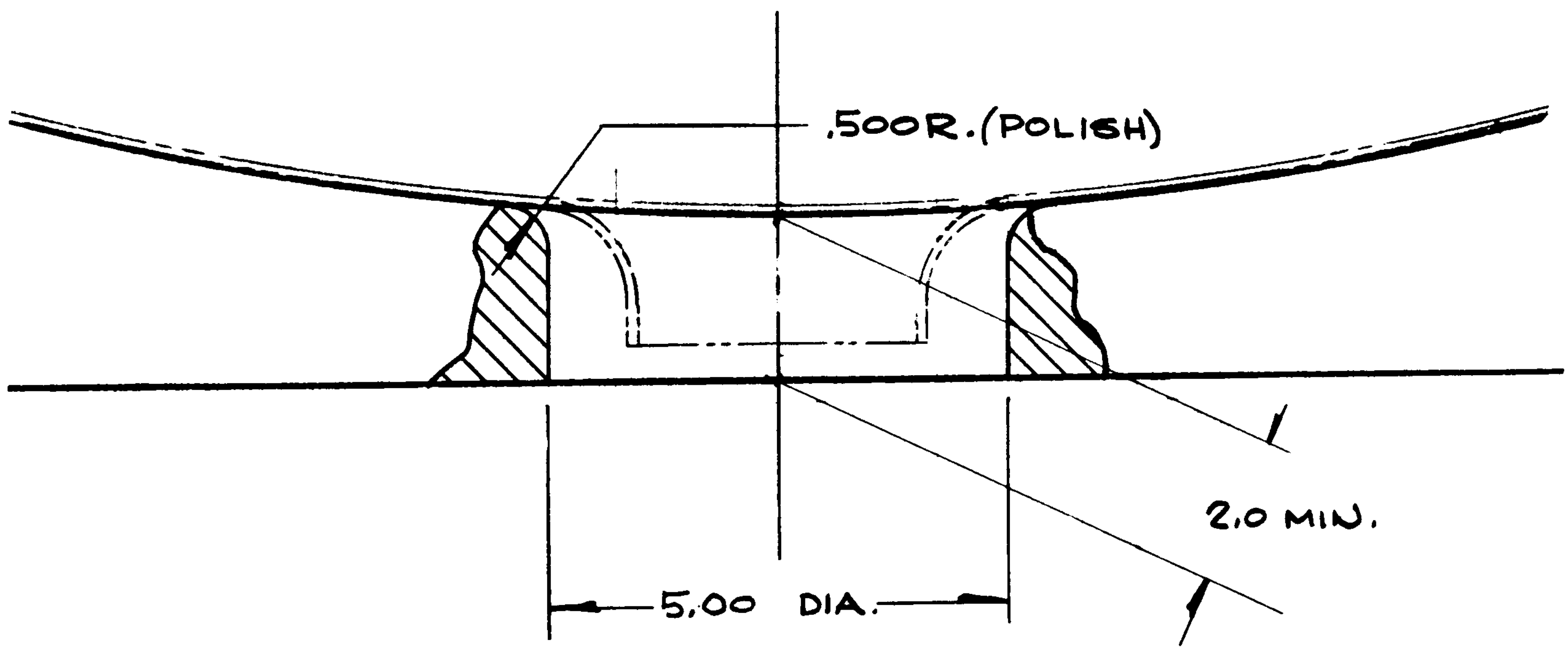


FIGURE 67. Section of 3-1/4-inch Diameter Port Form Block

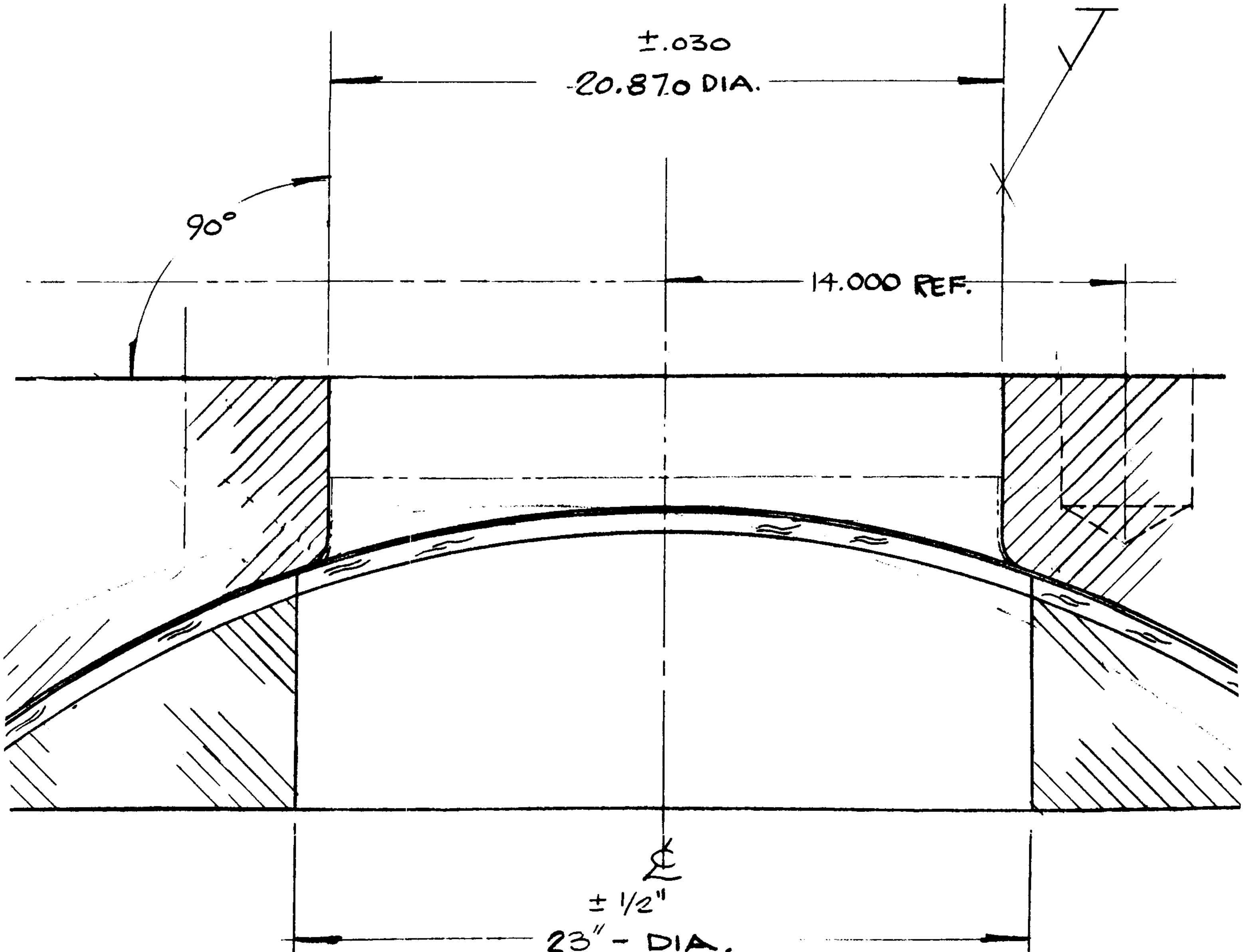


FIGURE 68. Section of Mated Kirksite Dies for Draw Forming 20-inch Diameter Ports

3. Sump Segment Support

The sump support is a female cast kirksite female form block made to match and nest the convex surface of the sump shell. It has a 5-inch clearance hole at the location of the port.

The equipment used in conjunction with the punches and supports were the hydraulic draw forming machines used in prior programs. For the 20-inch diameter ports, a horizontally mounted 400-ton capacity draw form machine was used (Figure 69). A smaller 90-ton capacity vertically mounted draw form machine was used for the 3-1/4-inch diameter ports (Figure 70).

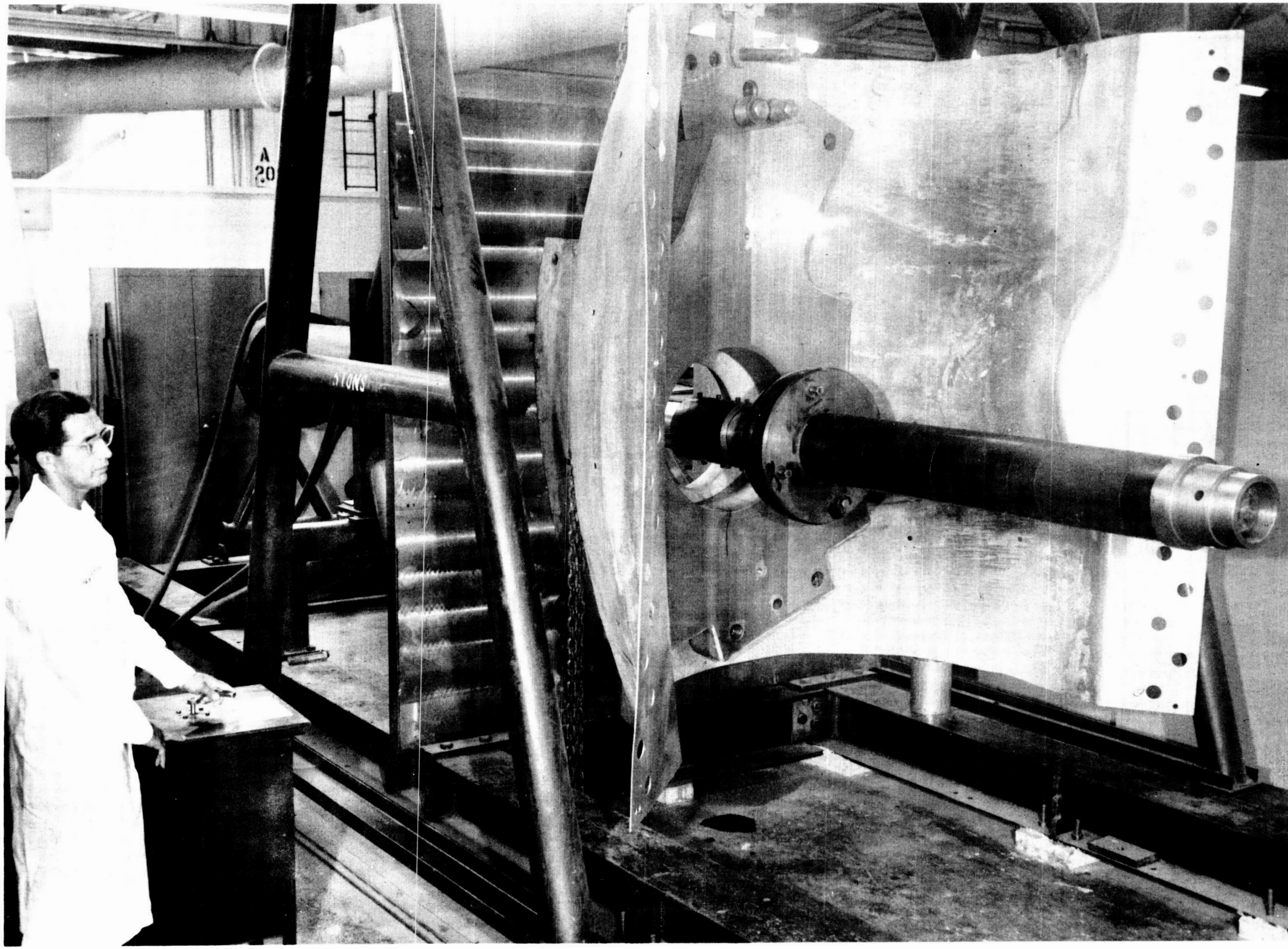


FIGURE 69. Hydraulic Draw Forming Equipment for 20-inch Diameter Ports MR4201

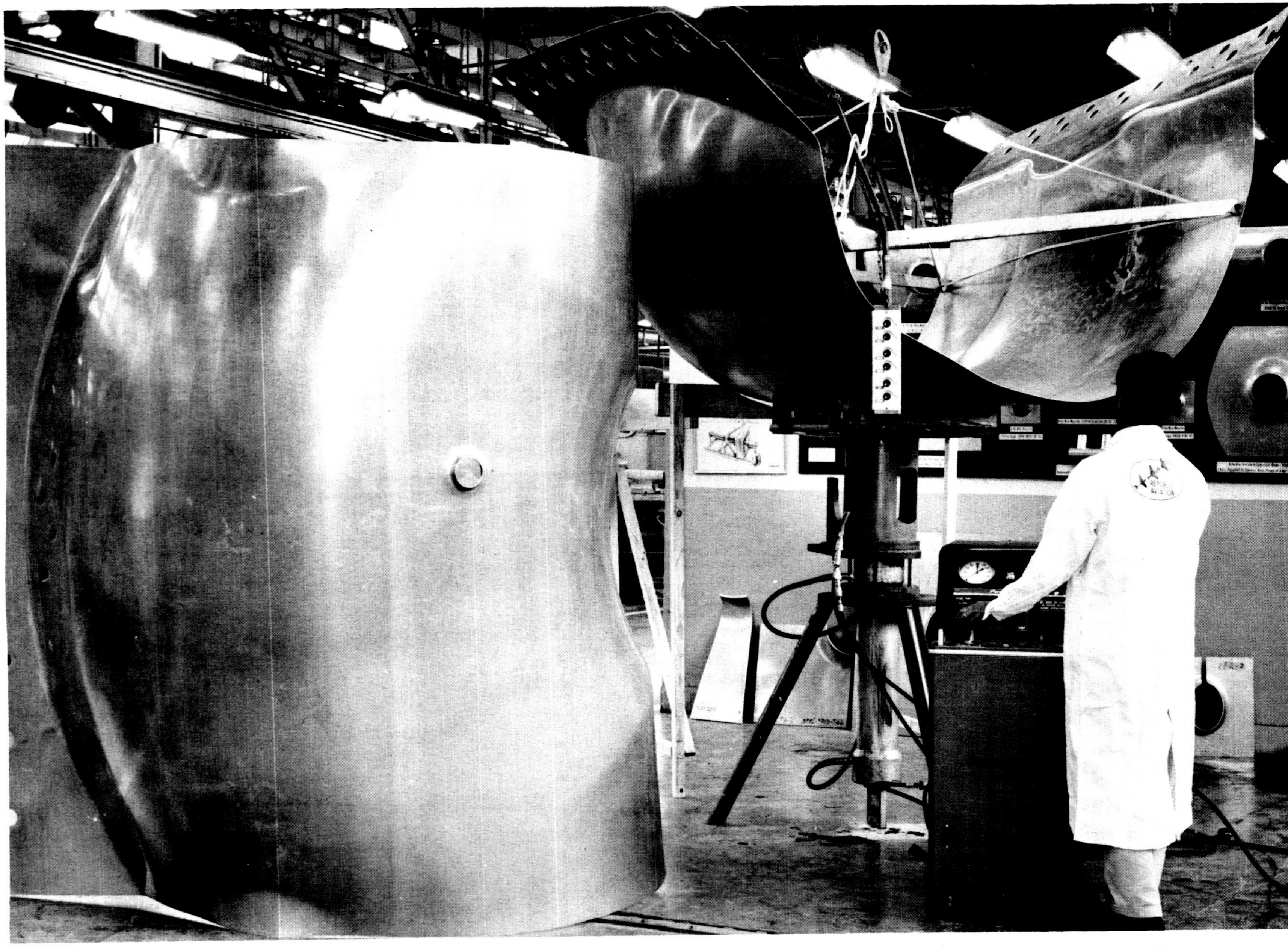


FIGURE 70. Hydraulic Draw Forming Equipment for Drawing 3-1/4-inch Diameter Ports
MR4209

C. PORT FORMING TESTS

A series of preliminary forming tests were run to determine optimum geometry for the 3-1/4-inch diameter ports in the upper gore segments and sump shell sections of the torus tank. The test utilized flat blanks, 10-inches by 10-inches square, to simulate the gore segments and semi-cylindrical blanks of 7-inch radius to represent the sump shells. Metallurgical considerations made it preferable that the forming be done at room temperature, but the test results indicated that this was only possible in the case of the gore segments providing (1) the material was in the annealed or solution heat treated condition (natural aging not to exceed three days at room temperature) and (2) that a maximum port tangent flange length of .88-inch was acceptable. For this flange height, the material gage thinned out to .098-inch. As can be seen in Table 7, higher flanges can be obtained through the use of elevated temperature forming.

Hot forming was mandatory for the port forming operation in the sump shells since ports of sufficient flange height could not be formed without the aid of heat in the curved test specimens (reference Table 8). Figures 71 and 72 show gage thickness at various points in the port flange of the test specimens.

The hot forming tests were accomplished by preheating the punch to approximately 750° F and placing it in contact with the periphery of the preform cutout in the blank. Forming commenced once the blank temperature, measured from the edge of the cutout, was at 350° F.

Both sample parts and data were submitted to NASA for review and test resulting in a decision that a minimum flange height of .78-inch and a minimum flange thickness of .080-inch was satisfactory. In addition, it would be acceptable to form the ports in the sump section in the annealed condition at elevated temperature followed by solution heat treat and artificial aging.

One of the torus segments that had been used in the ceramic die temperature uniformity tests and heat treat performance trials was utilized to test the 20-inch diameter port forming tool. Mounting holes

TABLE 7. DATA FOR 3.25-INCH PORTS IN GORE SEGMENTS (1)

Material Condition	Blank Thick.	Preform Cutout Dia.	Port(2) Flange Height	Min. (5) Flange Thick.	Forming Temp.	Results
W-As Rec'd	.124	2.25	-	-	Room	Flange Splitting
W-As Rec'd	.125	2.25	-	-	Room	Flange Splitting
W-18 Hours	.121	2.25	.88	.098	Room	Good
W-24 Hours	.124	2.25	.88	.101	Room	Good
W-48 Hours	.123	2.25	.88	.098	Room	Good
W-72 Hours	.121	2.25	.88	.098	Room	Good
W-6 Days	-	2.25	-	-	Room	Flange Splitting
Annealed	-	2.00	-	-	Room	Flange Splitting
Annealed	.121	2.25	.88	.097	Room	Good
Annealed	.123	2.25	.88	.098	Room	Good
Annealed	.127	2.00	1.00	.092	(3)	Good
Annealed	.126	1.79	1.10	.084	(3)	Local Neck (4)
Annealed	.125	1.52	1.25	.075	(3)	Good

(1) Gore Segments simulated by flat blanks.

(2) After machining approximately .050" for leveling plane of port edge and removing radiused portion of preform cutout edge.

(3) Port area heated by conduction; punch preheated and placed on preform cutout at approximately 750°F, maximum blank temperature (measured 1/2-inch from edge of cutout) was 350°F - 25°F.

(4) Caused by unequal heating due to blank misalignment, this material failure can be disregarded.

(5) Stretch forming may cause an additional 10% material thinout.

TABLE 8. DATA FOR 3.25-INCH PORTS IN SUMP SHELLS (1)

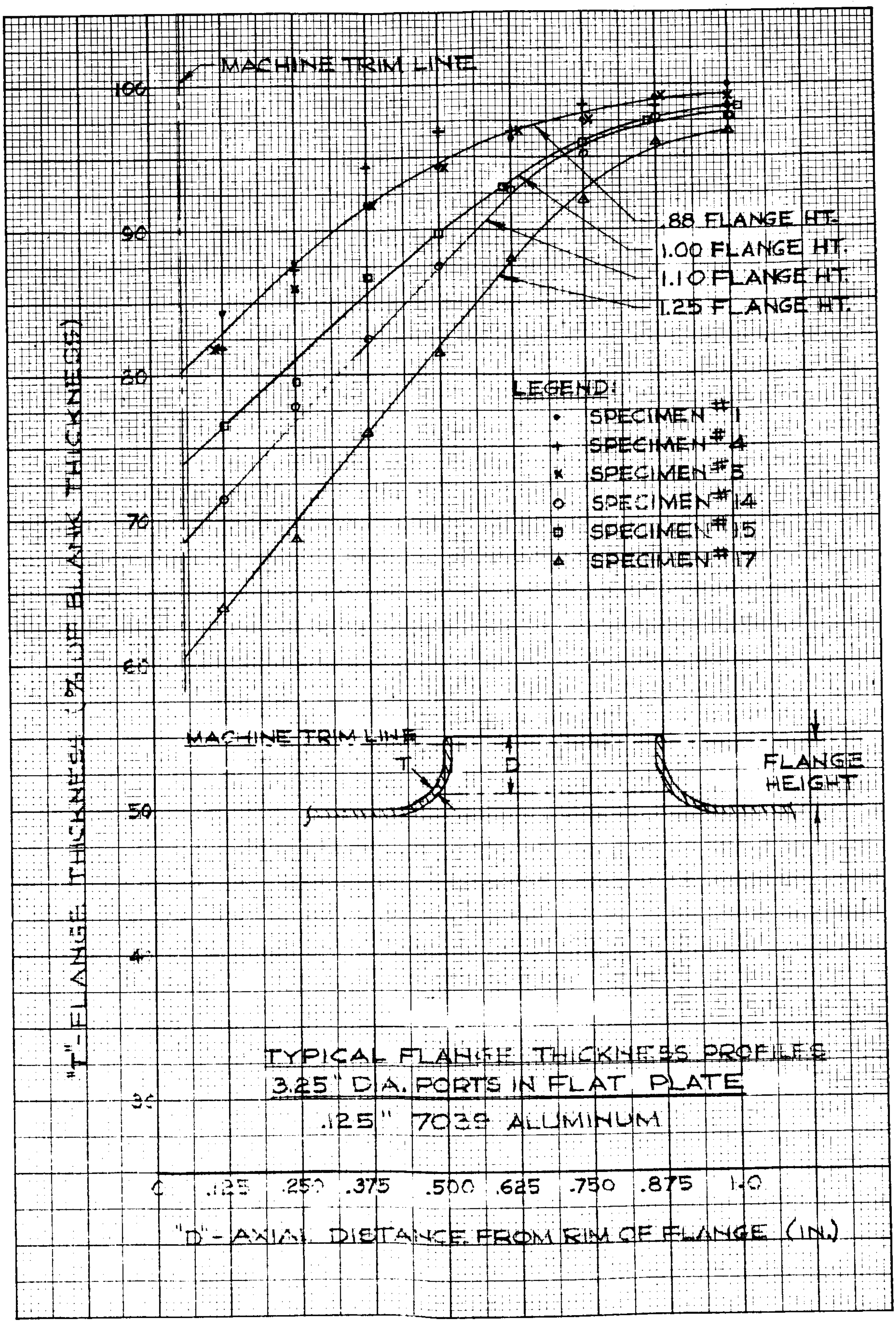
Material Condition	Blank Thick	Preform Cutout Major & Minor Dia.	Port(2) Flange Height	Variation(4) in Flange Thickness at Port Tip	Forming Temp.	Remarks
Annealed	-	2.79x2.45	-	-	Room	Insufficient flange height
Annealed	-	2.54x2.19	-	-	Room	Flange splitting
Annealed	.132	2.29x1.94	.68	.097x.109	(3)	Good
Annealed	.131	2.04x1.69	.78	.086x.101	(3)	Good
Annealed	.124	1.79x1.43	.90	.076x.090	(3)	Good
W-As Rec'd	.128	1.79x1.43	.90	.082x.096	(3)	Good

(1) Sump shells simulated by 7" radius, semi-cylindrical blanks.

(2) After machining approximately .050" for leveling plane of port edge and removing radiused portion of preform cutout edge.

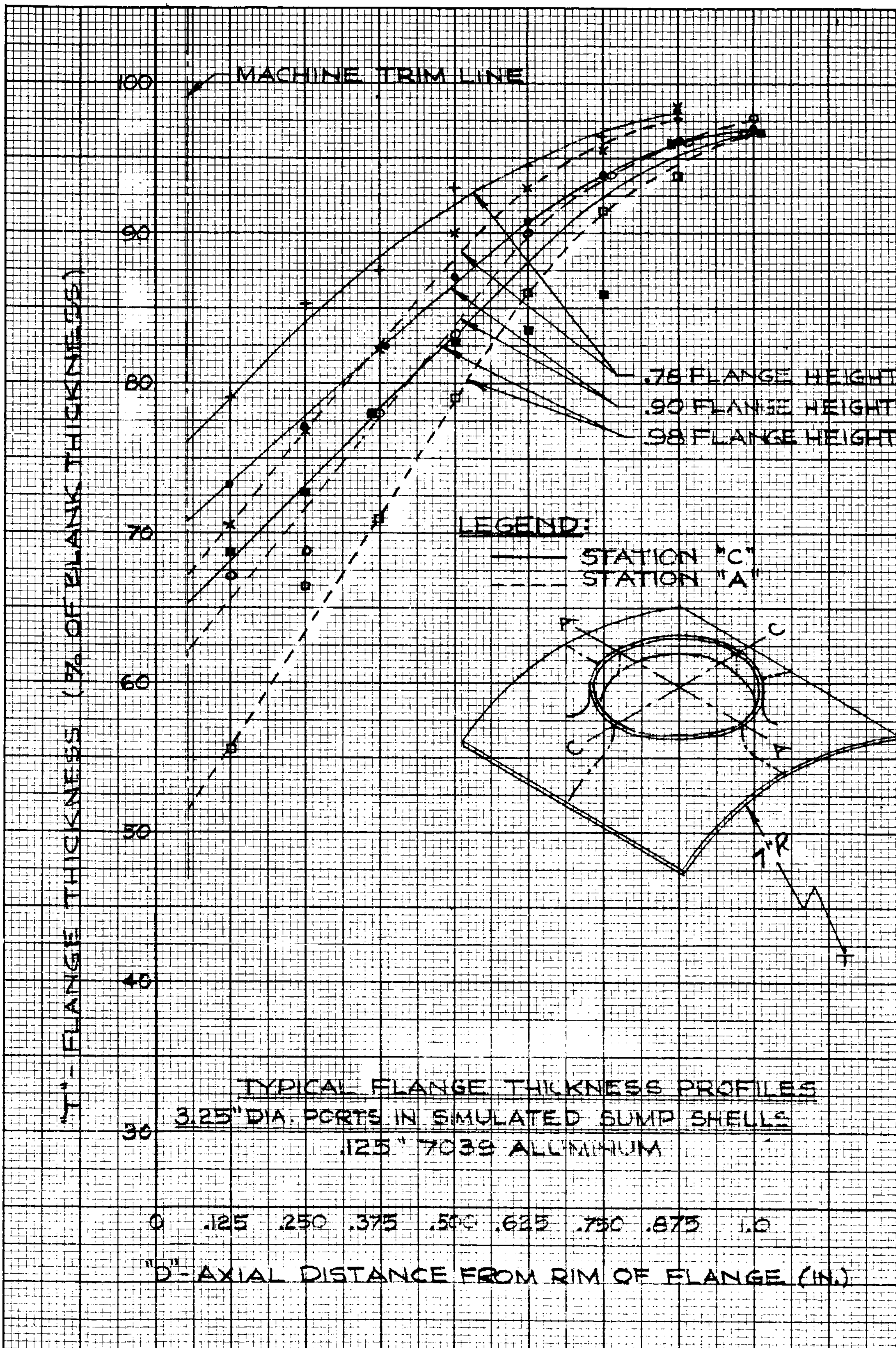
(3) Port area heated by conduction; punch preheated and placed on preform cutout at approximately 750°F; maximum blank temperature (measured 1/2-inch from edge of cutout) was 350°F - 25°F.

(4) Forming of the sump shells may cause additional material thinout.



MACHINE TRIM LINE
100
90
80
70
60
50
40
30
.88 FLANGE HT.
1.00 FLANGE HT.
1.10 FLANGE HT.
1.25 FLANGE HT.
LEGEND:
SPECIMEN #1
SPECIMEN #4
SPECIMEN #5
SPECIMEN #14
SPECIMEN #15
SPECIMEN #17
MACHINE TRIM LINE
T
D
FLANGE HEIGHT
"T" - FLANGE THICKNESS (% OF BLANK THICKNESS)
TYPICAL FLANGE THICKNESS PROFILES
3.25" DIA. PORTS IN FLAT PLATE
.125" 7039 ALUMINUM
.125
.250
.375
.500
.625
.750
.875
1.0
"D" - AXIAL DISTANCE FROM RIM OF FLANGE (IN.)

FIGURE 71



MACHINE TRIM LINE
100
90
80
70
60
50
40
30
"T" - FLANGE THICKNESS (% OF BLANK THICKNESS)
.78 FLANGE HEIGHT
.90 FLANGE HEIGHT
.98 FLANGE HEIGHT
LEGEND:
STATION "C"
STATION "A"
A
C
C
A
7"R
TYPICAL FLANGE THICKNESS PROFILES
3.25" DIA. PORTS IN SIMULATED SUMP SHELLS
.125" 7039 ALUMINUM
0 .125 .250 .375 .500 .625 .750 .875 1.0
"D" - AXIAL DISTANCE FROM RIM OF FLANGE (IN.)

FIGURE 72

were drilled while the skin was located on the combination trim and check fixture. The preform cutout was scribed, the hole cut, and the edges refined. The port was then located in the gore segment support and firmly attached to the draw forming machine and the spherical punch drawn through the cutout.

The machine and tools performed well, but there was a failure in the port flange where cracking occurred. This was not considered to be a representative part but was used primarily to check out the equipment and tooling since this part had been repeatedly exposed to thermal cycling during the tryout of the ceramic die.

A torus tank segment that had been formed, solution heat treated, and was in the "W" plus natural age condition was used in the next forming test. The port was successfully formed in this part with a flange height 1/4-inch in excess of the nominal dimension, providing sufficient material for a final trim operation. The springback in the material was not as great as had been anticipated and the resulting port opening was too large requiring the machining of the forming plug to a smaller diameter.

The port forming trials described above served to:

1) Prove out the tooling and equipment
2) Establish the correct cutout perimeter for each port configuration
3) Determine the necessary forming temperature parameters
4) Show the effects of different lubricants on the forming operation
5) Define the material condition necessary for successful port forming

Subsequent to these tests and the required modification to the cutout perimeters and the diameters of the spherical punches, the 3-1/4-inch and 20-inch diameter flared ports were formed in the torus tank gore segments and the sump segments for delivery to the customer.

After forming of the ports, the gore segments were remounted on the drape form die for the artificial age forming operation. Insulating material was packed in and around the port opening to minimize heat loss and assure a uniform temperature throughout the part.

The solution heat treat and aging cycles for the sumps were accomplished in a furnace after the port forming operation.

In Figures 73 and 74 are shown the gore segments and sump shell containing the flared ports.

D. DISCUSSION

The preliminary tests indicated that the 20-inch diameter flared ports could be formed at room temperature while the material was in the "W" or solution heat treated but not aged condition. The forming of the 3-1/4-inch diameter ports in the gore segments in the "W" condition and in the sump shells in the annealed condition could only be accomplished at elevated temperatures.

The method employed was simply to heat the forming plug to 750° F in a furnace and let it dwell on the preform cutout until the part adjacent to the plug reached a temperature of 350°F. The plug was then successfully drawn through the cutout.

To facilitate the movement of the plug through the cutout and to minimize galling, a high temperature lubricant (Fisk 604) was applied to both plug and port. This was done for both 20-inch and 3-1/4-inch ports.

Dimensional checks were made of the port openings, the flange heights, and the flange thickness with results tabulated in Table 9. In addition, Figures 76 through 79 depict the variation in flange thickness for three representative 20-inch diameter ports with readings taken at different positions and at varying distances from the flange lip as shown in Figure 75.

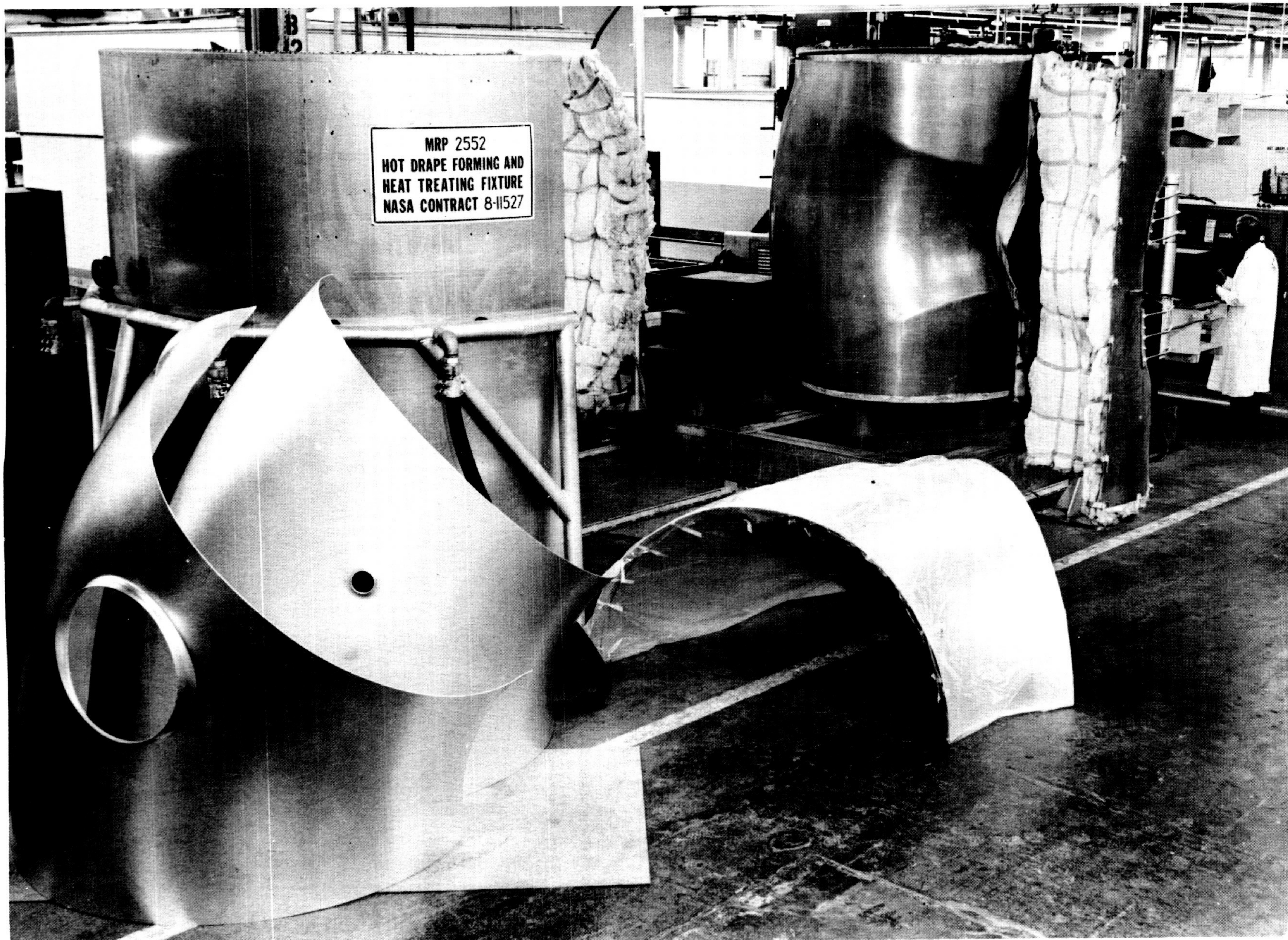


FIGURE 73. Gore Segments with both 20-inch and 3-1/4-inch Diameter Ports

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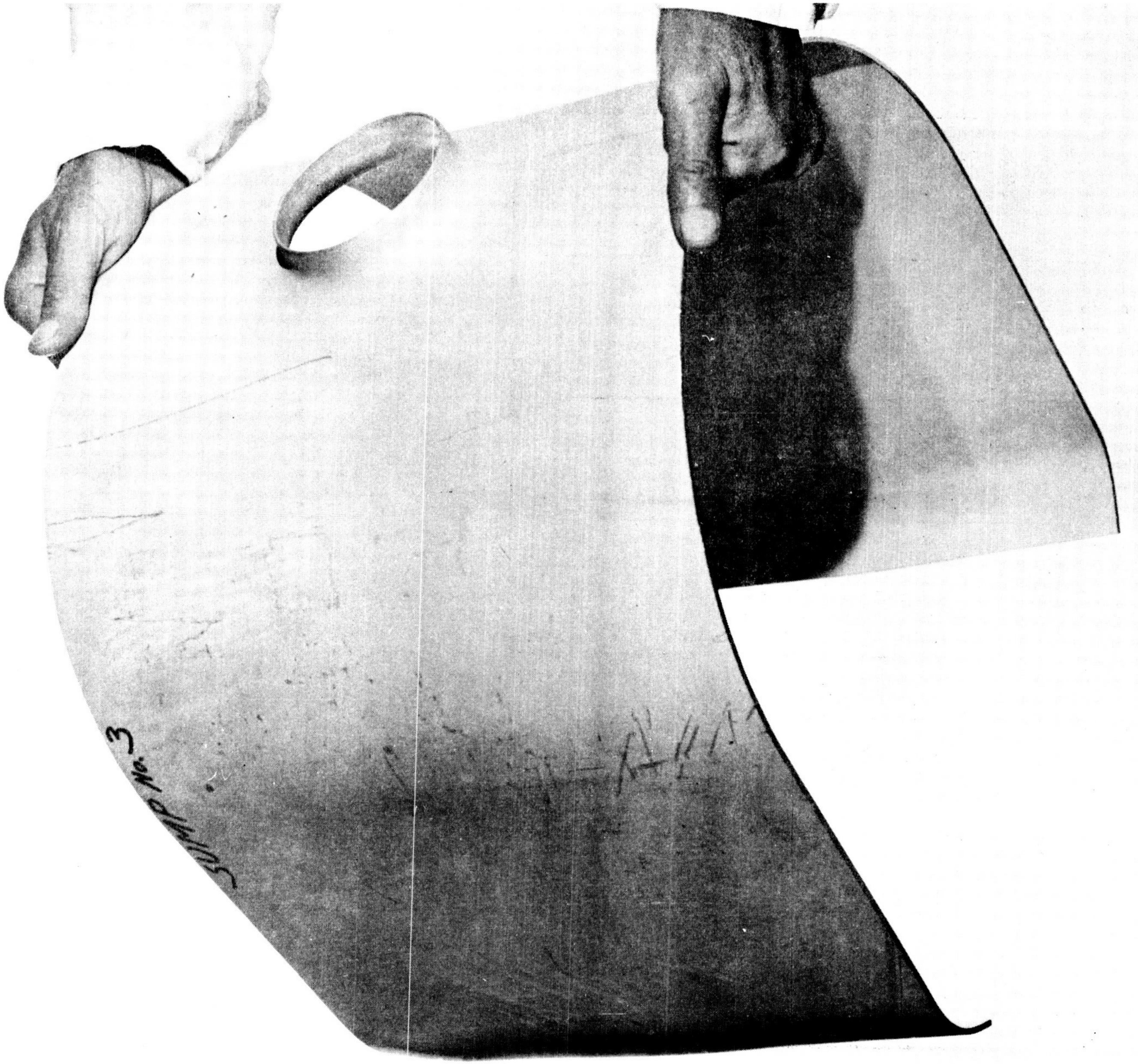


FIGURE 74. Sump Shell with 3-1/4-inch Diameter Flared Port MR4293

TABLE 9. TORUS TANK GORE SEGMENTS

Size Port (in.)	Part No.	Inside Dim. (inches)		Flange Height (inches)		Flange Thickness* (inches)	
		Max.	Min.	Max.	Min.	Max.	Min.
3-1/4	23	3.269	3.250	1.09	1.04	.098	.088
3-1/4	24	3.276	3.245	1.12	1.07	.100	.097
3-1/4	25	3.277	3.255	1.09	1.02	.096	.091
3-1/4	31	3.266	3.251	1.07	1.02	.102	.090
3-1/4	32	3.260	3.251	1.10	1.04	.099	.094
20	20	20.050	19.950	2.825	1.210	.110	.105
20	21	20.062	19.950	2.865	1.213	.108	.103
20	22	20.066	19.948	2.985	1.225	.113	.104
20	26	20.055	19.967	2.935	1.272	.114	.108
20	29	20.010	19.964	2.824	1.235	.104	.098
20	30	20.040	19.968	2.800	1.158	.101	.109
20	33	20.038	19.952	2.925	1.375	.105	.099
20	34	20.083	19.952	2.925	1.355	.110	.098

*Flange thickness at tip

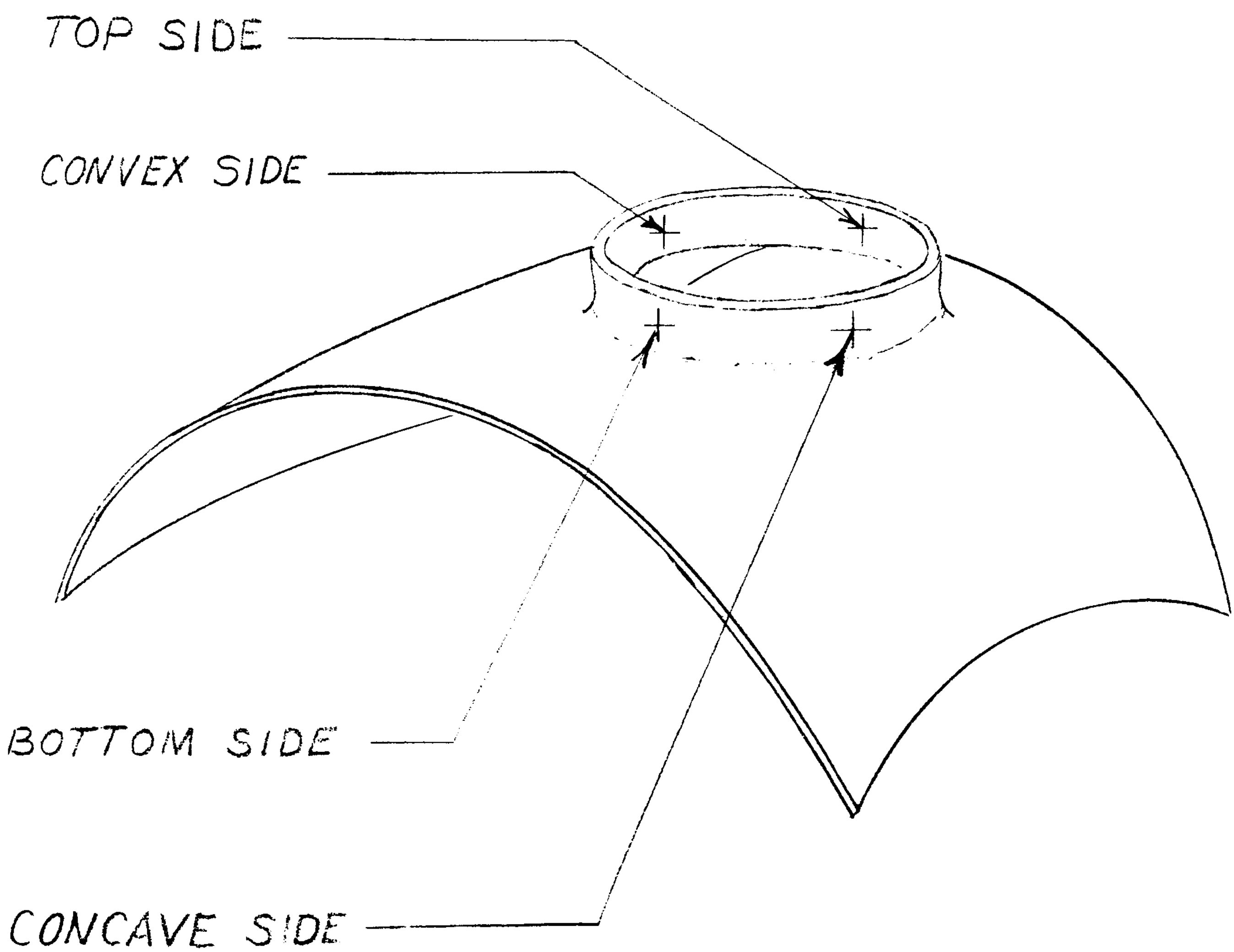
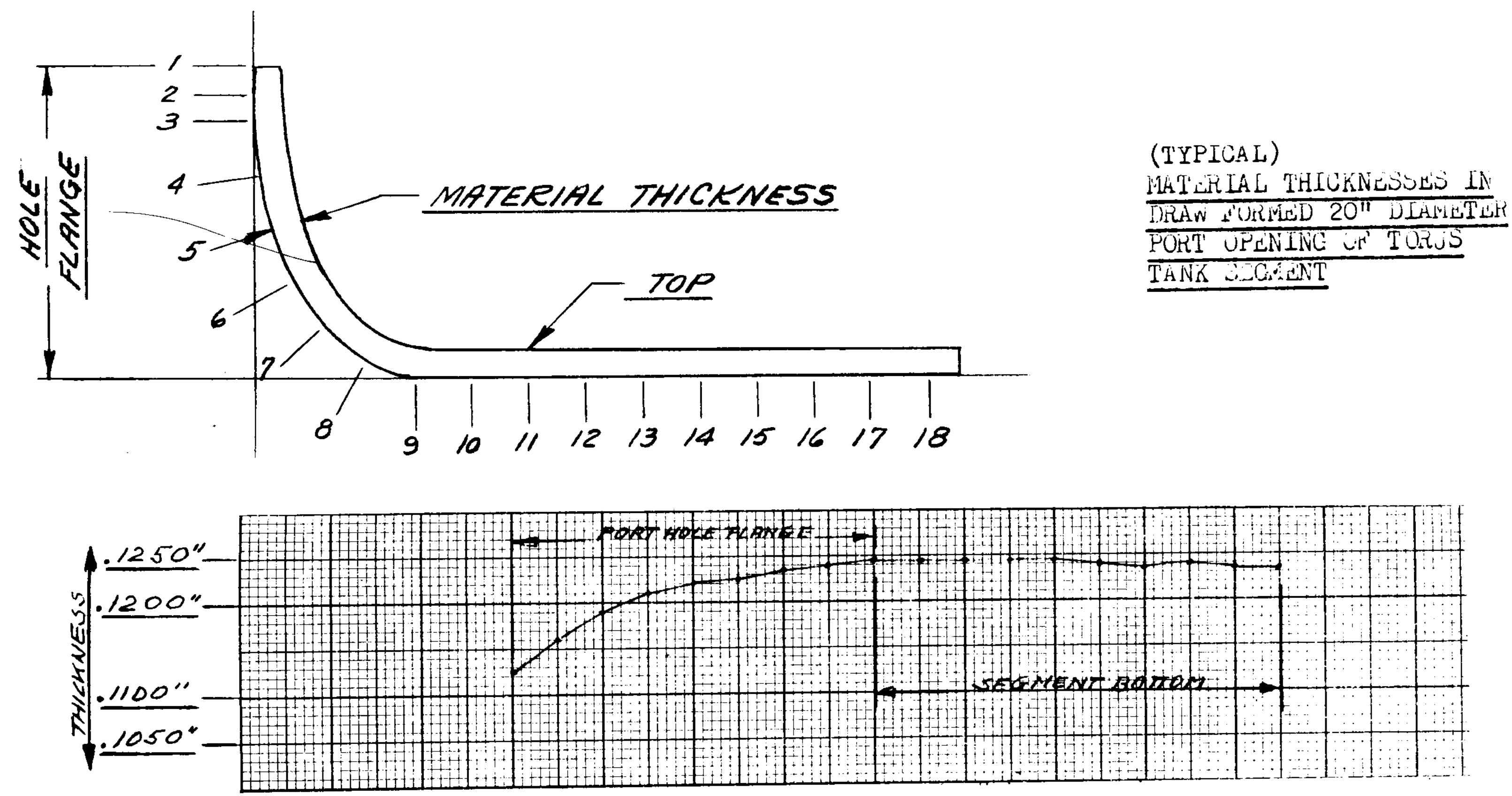
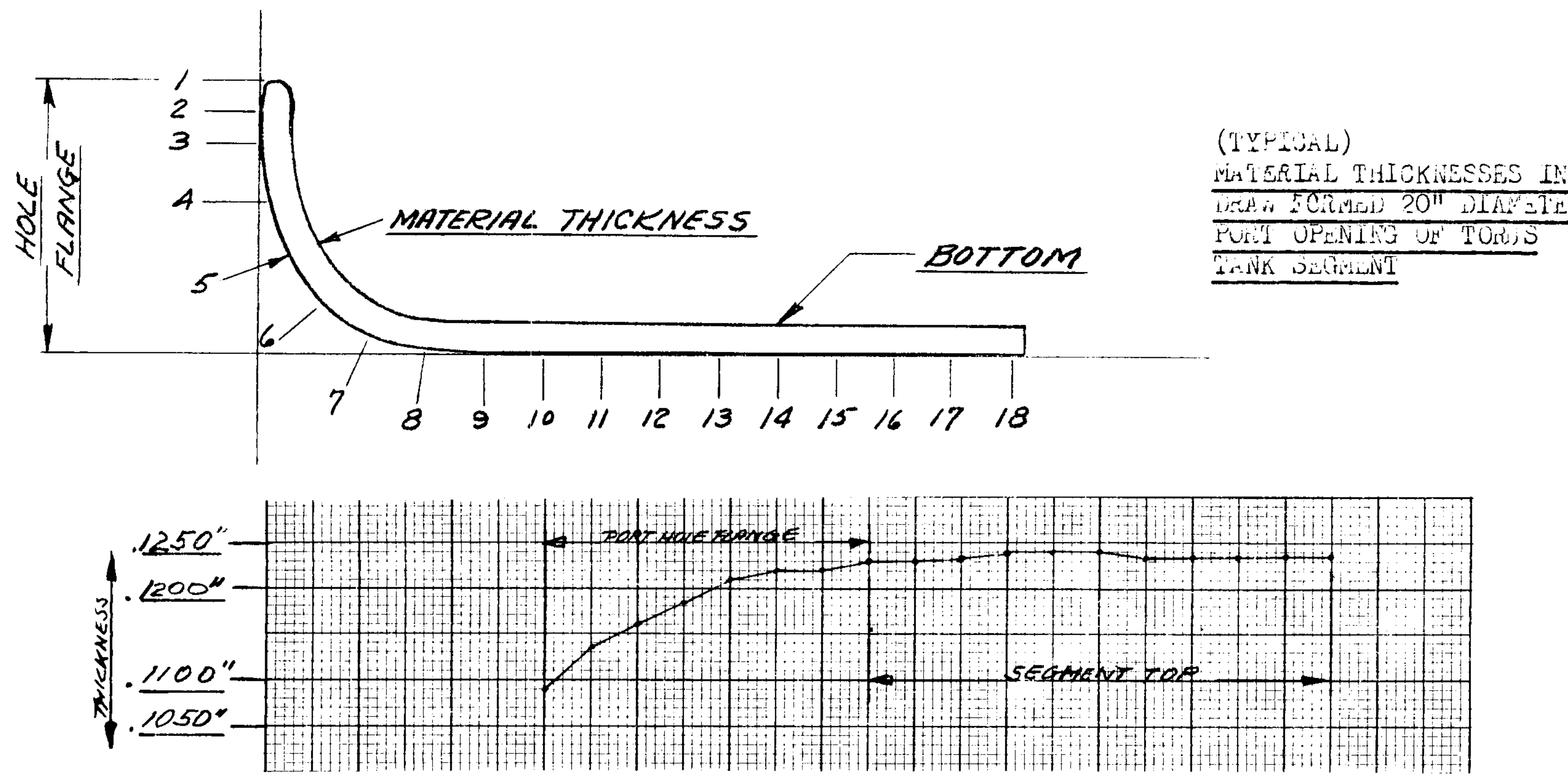


FIGURE 75. Position of Thickness Readings Given in Figures 76 through 79



	THICKNESS MEASUREMENTS																	
SPECIMENS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	.1125	.1155	.1190	.1210	.1220	.1230	.1235	.1240	.1245	.1240	.1245	.1240	.1245	.1240	.1235	.1235	.1235	.1235
2	.1130	.1165	.1185	.1210	.1220	.1220	.1235	.1240	.1240	.1245	.1245	.1245	.1245	.1240	.1240	.1240	.1235	.1235
3	.1125	.1160	.1190	.1210	.1220	.1220	.1235	.1240	.1245	.1245	.1245	.1245	.1245	.1240	.1235	.1240	.1235	.1240

FIGURE 76. Typical Material Thicknesses in Draw Formed 20-inch Diameter Port Opening of Torus Tank Segment



	THICKNESS MEASUREMENTS																	
SPECIMENS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	.1100	.1145	.1170	.1195	.1210	.1220	.1220	.1230	.1235	.1235	.1235	.1240	.1240	.1235	.1235	.1240	.1240	.1235
2	.1090	.1130	.1155	.1185	.1210	.1215	.1220	.1230	.1235	.1235	.1240	.1235	.1240	.1240	.1235	.1235	.1235	.1235
3	.1110	.1135	.1160	.1185	.1205	.1220	.1220	.1225	.1235	.1235	.1240	.1240	.1235	.1235	.1235	.1235	.1235	.1235

FIGURE 77. Typical Material Thicknesses in Draw Formed 20-inch Diameter Port Opening of Torus Tank Segment

CONVEX SIDE	THICKNESS MEASUREMENTS											
SPECIMENS	1	2	3	4	5	6	7	8	9	10	11	12
1	.1035	.1045	.1070	.1085	.1100	.1115	.1125	.1140	.1155	.1170	.1180	.1175
2	.1030	.1045	.1060	.1085	.1100	.1110	.1125	.1135	.1150	.1160	.1170	.1175
3	.1040	.1060	.1075	.1090	.1110	.1115	.1130	.1140	.1150	.1160	.1170	.1160

CONVEX SIDE	THICKNESS MEASUREMENTS											
SPECIMENS	13	14	15	16	17	18	19	20	21	22	23	24
1	.1175	.1185	.1180	.1180	.1180	.1180	.1180	.1170	.1165	.1160	.1160	.1165
2	.1170	.1170	.1170	.1180	.1175	.1175	.1170	.1160	.1150	.1150	.1155	.1155
3	.1160	.1170	.1165	.1170	.1165	.1165	.1155	.1140	.1145	.1150	.1150	.1150

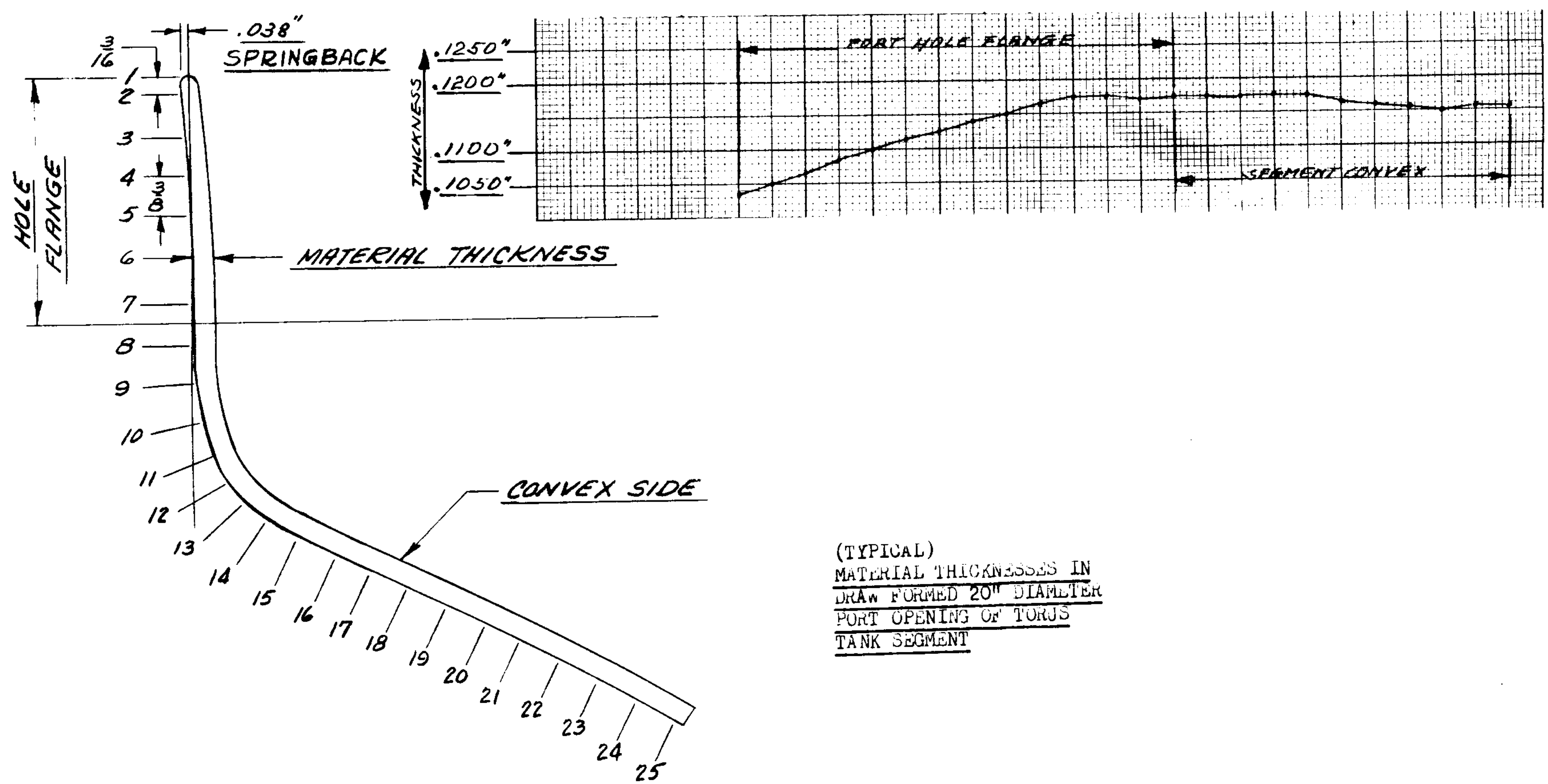
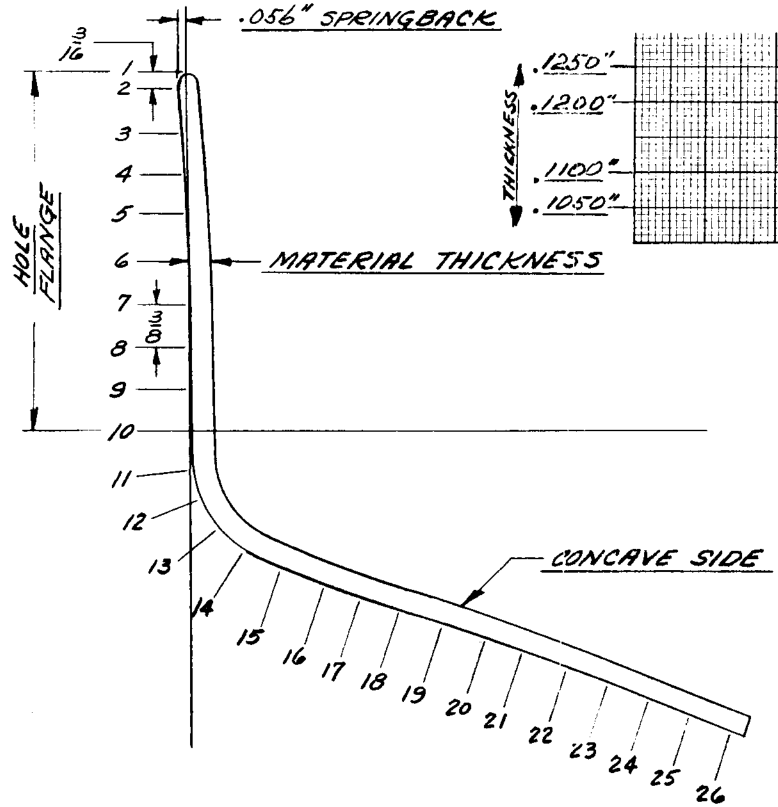
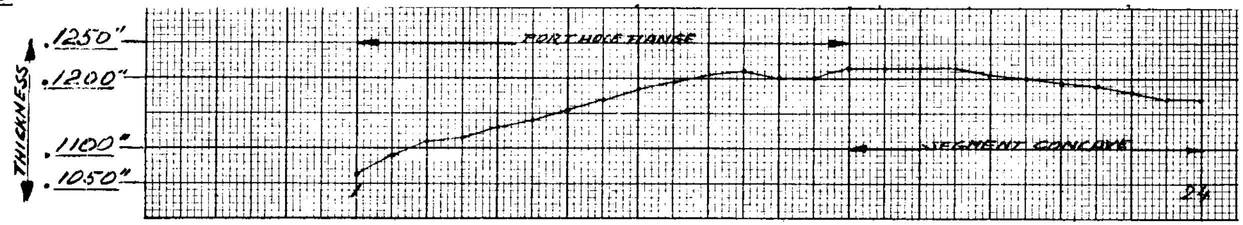


FIGURE 78. Typical Material Thicknesses in Draw Formed 20-inch Diameter Port Opening of Torus Tank Segment

CONCAVE SIDE	THICKNESS MEASUREMENTS																							
SPECIMENS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	.1080	.1090	.1110	.1115	.1125	.1140	.1150	.1165	.1180	.1195	.1200	.1210	.1200	.1200	.1220	.1215	.1210	.1210	.1200	.1200	.1195	.1190	.1180	.1170
2	.1065	.1080	.1095	.1115	.1130	.1140	.1150	.1170	.1180	.1195	.1200	.1210	.1200	.1200	.1210	.1215	.1215	.1215	.1210	.1200	.1190	.1190	.1180	.1170
3	.1070	.1090	.1110	.1120	.1140	.1145	.1160	.1170	.1185	.1195	.1210	.1210	.1205	.1215	.1225	.1220	.1210	.1210	.1200	.1200	.1195	.1185	.1180	.1170





(TYPICAL)
MATERIAL THICKNESSES IN
DRAW FORMED 20" DIAMETER
PORT OPENING OF TORUS
TANK SEGMENT

FIGURE 79. Typical Material Thicknesses in Draw Formed 20-inch Diameter Port Opening of Torus Tank Segment

CONCLUSIONS

The forming of flared port openings by the withdrawal of a punch through an undersize hole was proven to be applicable to the configuration and material of the ports.

A method of locally heating the workpiece in the area of the cutout during port forming is an improvement that would facilitate the procedure in those cases where elevated temperature forming is required.